

AD 744651

ENGINEERING EVALUATION  
STUDY OF  
ENVIRONMENTAL CONDITIONING SYSTEMS  
FOR  
HIGH PRESSURE RESEARCH VESSELS

FINAL REPORT

Contract No. N00014-72-C-0125

Office of Naval Research

U.S. Navy

By

John M. Canty  
Edward H. Lanphier  
Richard A. Morin

28 June 1972

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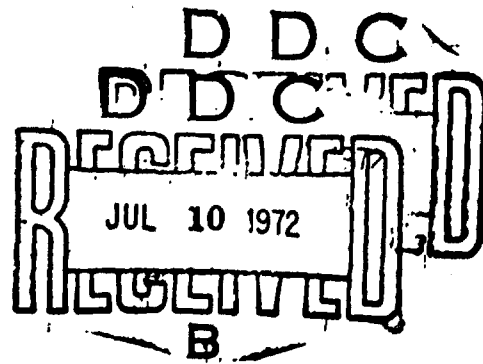
High Pressure Laboratory  
Department of Physiology  
State University of New York at Buffalo  
Buffalo, N.Y. 14214

The Research Foundation of State University of New York  
P.O. Box 7126, Albany, N.Y. 12224

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Engineering Evaluation  
study of  
ENVIRONMENTAL CONDITIONING SYSTEMS  
for  
High Pressure Research Vessels

by  
John M. Canty  
Edward H. Lanphier  
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Research sponsored by  
U. S. Navy  
The Office of Naval Research  
Contract No. N00014-72-C-0125  
Contract authority identification no.  
NR 291-052/10-7-71 (485)

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|--|--|--|
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| 1. ORIGINATING ACTIVITY (Corporate author)<br>State University of New York at Buffalo<br>(The Research Foundation of State University<br>of New York, P.O. Box 7126, Albany, N.Y.)   |  | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified |
|  |  | 2b. GROUP<br>---                                   |
| 3. REPORT TITLE<br>Engineering evaluation study of<br>ENVIRONMENTAL CONDITIONING SYSTEMS<br>for High Pressure Research Vessels   |  |  |
| 4. DESCRIPTIVE NOTES (Type of report and inclusive dates)<br>Final report covering the period 1 February 1972 to 31 May 1972   |  |  |
| 5. AUTHOR(S) (Last name, first name, initial)<br>Canty, J. M., Lanphier, E. H., and Morin, R. A.   |  |  |
| 6. REPORT DATE<br>28 June 1972   | 7a. TOTAL NO. OF PAGES<br>77   | 7b. NO. OF REFS<br>27                              |
| 8a. CONTRACT OR GRANT NO.<br>N00014-72-C-0125  | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>None                                      |  |
| b. PROJECT NO.   |  |  |
| c.   | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned<br>this report) |  |
| d.   | None   |  |
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| 13. ABSTRACT<br>Several systems were reviewed including low temperature condensation and adsorption as well as the use of soda lime. The results indicate that low temperature condensation of CO <sub>2</sub> might be attractive for pressures up to 30 atmospheres. However, the large refrigeration requirement will probably preclude this technique at very high pressures. Adsorption systems seem to be very attractive but require careful design of the adsorbent bed at high pressures due to the low diffusivity of the gas.<br><br>Although the information is presented in a general way, the main purpose of this investigation was to select a system for the 170 atmosphere High Pressure Research Facility at the Department of Physiology - State University of New York at Buffalo. A combination low temperature dehumidification followed by low temperature adsorption of water then adsorption of carbon dioxide appears to be best suited for this application.<br><br>Data and references are included in the report to permit the reader to evaluate other design conditions. |  |  |

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## INTRODUCTION

A new high pressure research chamber has been provided by the office of Naval Research for the high pressure section of the Laboratory of Environmental Physiology in the Department of Physiology, State University of New York at Buffalo. This chamber has two compartments suitable for human occupancy and a working pressure of 170 atm abs, 2500 psig, or 5,600 ft. of equivalent sea water depth.

Except for experiments at relatively low pressures, utilizing compressed air for pressurization and ventilation, operation of such a chamber for human or animal studies requires an environmental conditioning system. Such a system must remove carbon dioxide and various gaseous contaminants, must provide for maintenance of the desired partial pressure of oxygen, and must ensure suitable temperature, humidity and circulation of the chamber atmosphere.

All of these requirements are important, but the means employed for removal of CO<sub>2</sub> is the central and most crucial component of most practical environmental control systems. Almost without exception, removal of CO<sub>2</sub> from high pressure research chambers has been accomplished by chemical adsorption utilizing soda lime or Baralyme R\*. Although usually providing a satisfactory means of CO<sub>2</sub> removal, the use of a granular absorbent presents several problems. Most important is the fact that a relatively large volume of material must be replaced at quite frequent intervals.

In a chamber occupied by human subjects, pre-packed canisters of adsorbent can be passed in and out through an access lock and utilized in a basically simple and inexpensive internal scrubbing system. The main defect of this arrangement is that incapacitation of the occupants or malfunction of the lock or scrubber could cause a life-threatening crisis. An "external loop" system avoids such potential hazards and is also suitable for maintaining the chamber atmosphere during animal studies.

An external environmental control system must include at least one significant vessel, with working pressure equal to that at which the chamber will be used, to hold the adsorbent. This (or these) must be very readily opened for rapid replacement of the material. Other components of the environmental conditioning system may or may not be provided externally. In any case, the vessels and accompanying large-bore valves, piping and connections inevitably become items of major cost especially in a system of 2500 psig working pressure.

\*(indicates registered trademark)

In considering an environmental conditioning system for the new Buffalo chamber, we felt strongly that the usual approaches left much to be desired and that this warranted open-minded consideration of other possibilities. Our major objective was to develop, if possible, a system that combined the simple and inexpensive structures of an internal loop with total, or almost total, capability for operation and control from the outside of the chamber. In addition, we were intent upon providing a secondary system that could be put into operation from the outside in the event of failure of the primary system.

Our proposal for an engineering feasibility study of environmental control systems, which led to the present work, involved consideration of four concepts that had seldom or never been applied in high pressure research chambers. One of these concepts was the use of a compact countercurrent heat exchanger for dehumidification and temperature regulation. Two relatively uncommon approaches to CO<sub>2</sub> removal were included. One of these was use of low temperature in a multistage countercurrent heat exchange system. The other employed adsorption of CO<sub>2</sub> with synthetic zeolites and periodic in-situ regeneration of the adsorbent. The fourth concept employed familiar chemical CO<sub>2</sub> adsorption but made use of the unusual pass-through lock design of the Buffalo Chamber for a system intended primarily for emergency use.

Although the primary motive of the study was to determine the most promising approaches to environmental conditioning for the new Buffalo chamber, we believe that this report will be useful in several other connections. We have made a particular effort to provide an instructive document applicable to many aspects of environmental conditioning in high pressure atmospheres.

## I. Physiological Requirements

The design of a system to control the environmental parameters of a chamber must be predicated on certain assumptions for the rate of change of temperature and gas constituents. For short term operation, the major concern is the products of respiration from the chamber occupants. When using recirculation and purification systems, trace contaminants from outgassing of equipment, supplies and chamber occupants becomes more important as the time of exposure increases.

### A. Oxygen, Carbon Dioxide and Water Rates:

The main use of the High Pressure Research Facility at the State University of New York at Buffalo is to investigate physiological effects under various conditions of pressure and gas composition. These experiments would typically have two or more chamber occupants alternating between performing exercise (as the experimental subject) and monitoring the test. A man might, for example, have a daily routine equivalent to six hours of relatively heavy work, ten hours of light work and eight hours of sleep. Table 1 is a compilation of the respiratory gas exchange of such a schedule, assuming a respiratory quotient (R.Q.) of 0.85. This is probably a reasonable approximation for an active diving schedule as well but would be conservative for an extended decompression period where the daily  $\text{CO}_2$  production would only be about 2.2 #/day.

TABLE 1

| Work            | Metabolic Rate |             | Hours/<br>Day | $\dot{V}_{\text{CO}_2}$ |       |       | $\dot{V}_{\text{O}_2}$ |       |       | Respiratory<br>H <sub>2</sub> O |       |
|-----------------|----------------|-------------|---------------|-------------------------|-------|-------|------------------------|-------|-------|---------------------------------|-------|
|                 | Kcal/<br>Min   | BTU/<br>Hr. |               | l/min<br>STPD           | #/hr. | #/day | l/min<br>STPD          | #/hr. | #/day | #/hr.                           | #/day |
| Heavy           | 7.5            | 1800        | 6             | 1.5                     | .38   | 2.3   | 1.75                   | .18   | 1.08  |                                 |       |
| Light           | 2.5            | 600         | 10            | .5                      | .13   | 1.3   | 0.6                    | .061  | .61   |                                 |       |
| Sleep           | 1              | 240         | 8             | .25                     | .06   | .5    | .3                     | .023  | .18   |                                 |       |
| Daily Total/Man |                |             |               |                         |       | 4.1   |                        |       | 1.87  |                                 |       |

In addition to respiratory water there will be evaporation from the skin assumed to be about .8 liter of water per day (1.8#) or a total water vapor from the chamber occupants of about 3.7 lbs/man day.

It will be necessary to replace the oxygen consumed by the chamber occupants. Based on the values in Table 1, this will amount to about 35 SCF/man during the daytime and 4 SCF/man when sleeping.

Obviously this idealized model will not be duplicated exactly. However, the values give realistic design parameters to determine daily totals and maximum instantaneous rates of CO<sub>2</sub> production. For comparison, the heavy work specified in Table I would correspond to a booted diver wading at maximum speed on a muddy bottom or swimming with fins at a speed of 90 feet per minute. The metabolic levels are obviously much higher than those for space activity where the estimated CO<sub>2</sub> production is 2.1 to 2.3 #/man day and water production is .8 #/man day (Ref. 1, 2 and 3). There is some evidence that 4 lbs/man day is typical for long undersea exposure based on the experience in Tektite I (Ref. 4).

### B. Chamber CO<sub>2</sub> Equilibrium Pressure

#### 1. Determine CO<sub>2</sub> Loop flow given maximum CO<sub>2</sub> pressure:

Figure I-1 shows the chamber equilibrium CO<sub>2</sub> pressure versus flow rate through the CO<sub>2</sub> removal system for various work rates. This is valid for steady state conditions regardless of the vessel size. To find the required CO<sub>2</sub> loop flow with a known maximum level of CO<sub>2</sub> pressure enter the curve at the ordinate corresponding to the maximum CO<sub>2</sub> level desired and draw a horizontal line. For each level of activity multiply the number of occupants at that work level times the required loop flow. Add the flows to determine the recirculation rate required.

Example 1: Determine the recirculation rate for a three man team with one man doing heavy work and two occupied at light duty. The maximum desired CO<sub>2</sub> level is 4 mm Hg.

$$1 \times 10.7 + 2 \times 3.7 = 18 \text{ cfm}$$

This is shown on the horizontal dashed line on Fig. I-1.

#### 2. Determine CO<sub>2</sub> pressure for a known CO<sub>2</sub> loop flow:

Since most circulation loops operate at a constant flow it is possible to use Fig. 1 to evaluate chamber CO<sub>2</sub> pressures at varying conditions of occupant activity. This is done by entering the curve abscissa at the loop flow and drawing a vertical line. Add the CO<sub>2</sub> pressure contributed by each occupant.

Example 2: For the above case at 18 cfm flow, two men on light duty and one at heavy work the chamber equilibrium pressure would be:

$$1 \times 2.4 + 2 \times .8 = 4 \text{ mm Hg}$$

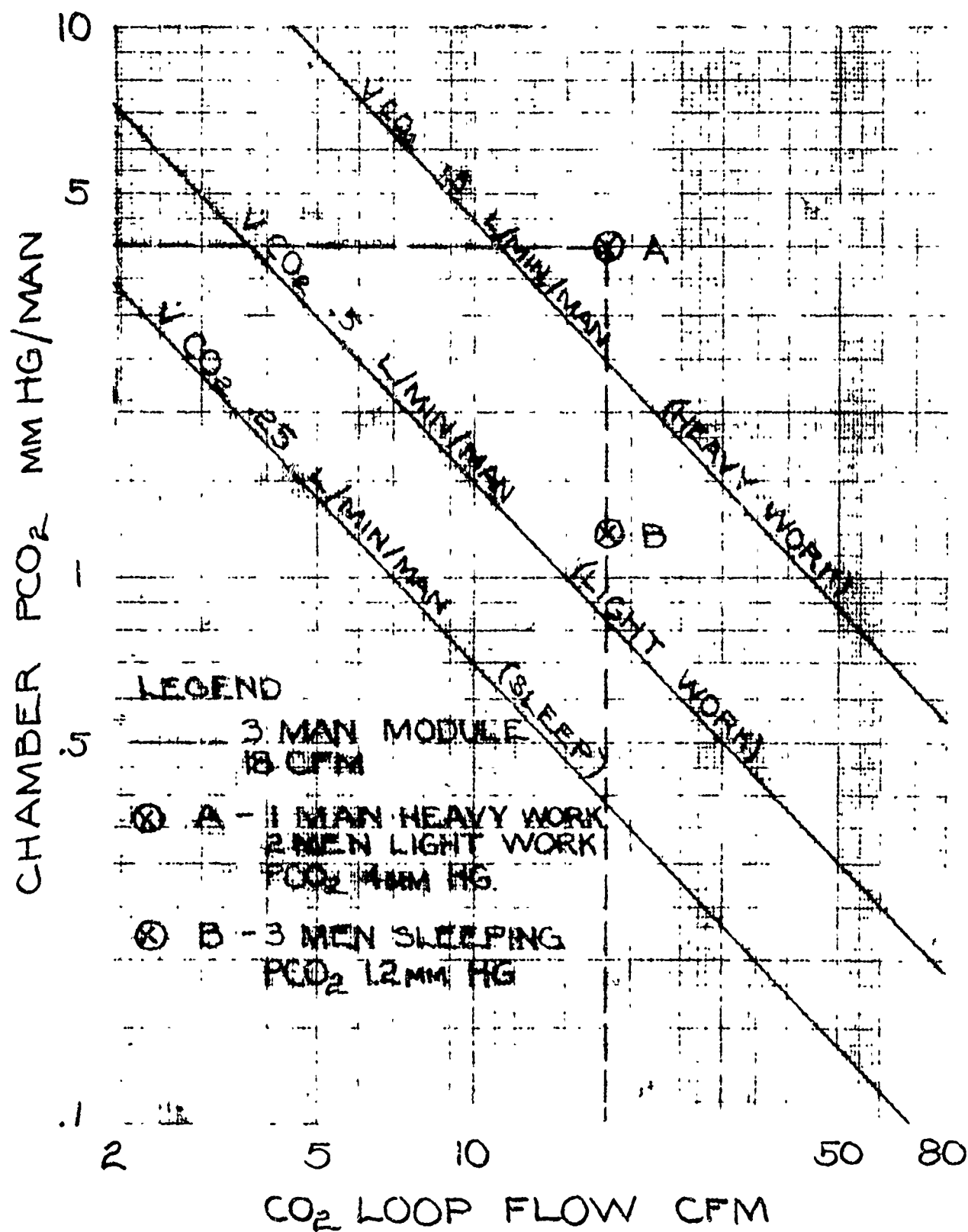


FIG. I-1

CHAMBER  $PCO_2$  VS. CO<sub>2</sub> LOOP FLOW

When all three men are sleeping the CO<sub>2</sub> pressure would approach:

$$3 \times .39 = 1.2 \text{ mm Hg}$$

This is shown on the vertical dashed line on Fig. I-1

Note: The curves in Figure I-1 are based on complete removal of CO<sub>2</sub> in recirculation loop. While this is a valid assumption for most systems the rates and equilibrium pressures must be adjusted if only part of the CO<sub>2</sub> is removed by adding the exit pressure of CO<sub>2</sub> to the value given in Fig. I-1.

Figure I-2 has curves showing the increase in CO<sub>2</sub> level as a function of time, for the SUNYAB High Pressure Research Facility if the CO<sub>2</sub> removal system is out of service or not functioning properly. It is obvious that, especially in the smaller compartment, the CO<sub>2</sub> level will become prohibitively high in a short period of time, less than one hour with 3 men awake but not overly active (Curve B). It is certainly possible to have very high CO<sub>2</sub> production rates for short periods of time. In physiological measurements of maximum oxygen uptake, this could reach 4 liters of CO<sub>2</sub>/minute for perhaps ten minutes. This gas would normally flow to measuring devices which would have separate CO<sub>2</sub> removal means. However, if the CO<sub>2</sub> was allowed to flow into the chamber this would be an excess of 2.5 liters (over the 1.5 l/min assumed for heavy work). The rate of CO<sub>2</sub> pressure increase would follow curve A in Fig. I-2 or after 10 minutes the pressure would increase by 4 mm Hg. This is not considered a problem.

The change (decrease) in oxygen partial pressure will be approximately the same as shown in Fig. I-2 for CO<sub>2</sub> (increase). Since the normal operating level for O<sub>2</sub> will be over 150 mm Hg, a uniform control of the oxygen makeup is much less critical than for CO<sub>2</sub> removal.

### C. Humidity Control

Figure I-3 shows the amount of water removed per hour as a function of the flow through the water loop. There is some indication that a relative humidity of about 50% is desirable from the standpoint of diver comfort. However, there has been little study on the effect of varying the humidity at high pressures.

From Figure I-3 it can be seen that if an 18 cfm loop is used for a three man chamber, to maintain a low CO<sub>2</sub> level, the humidity level will drop well below 50%. As noted in part I-A the expected H<sub>2</sub>O vapor production is 3.7 #/man day or about 11# total. Thus in an 18 cfm system the "average" R.H. will be about 25%. This can be remedied by periodically reversing the flow and evaporating the

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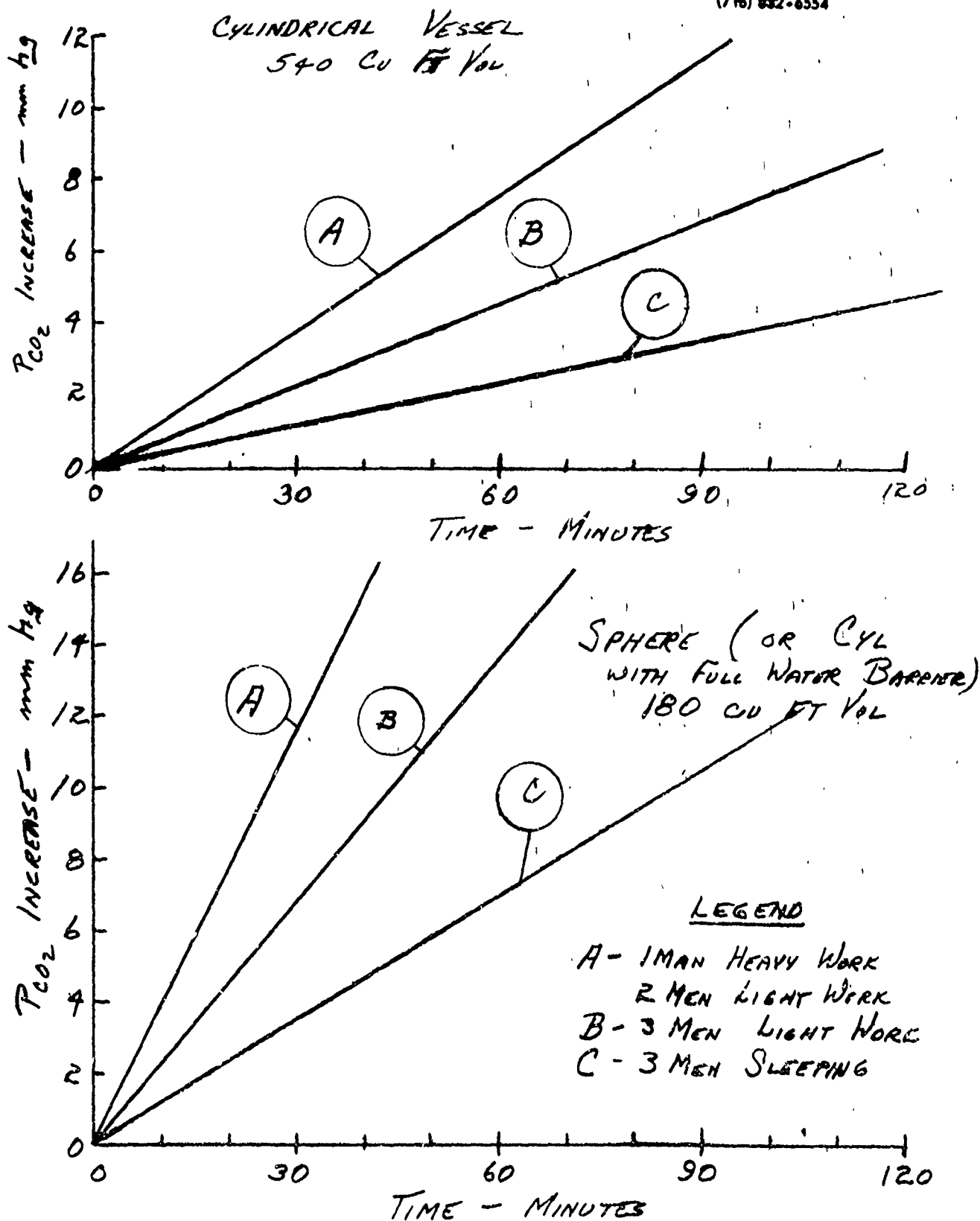


FIG I-2



TITLE: MOISTURE REMOVED IN WATER  
LOOP & FLOW & RELATIVE HUMIDITY

I-6

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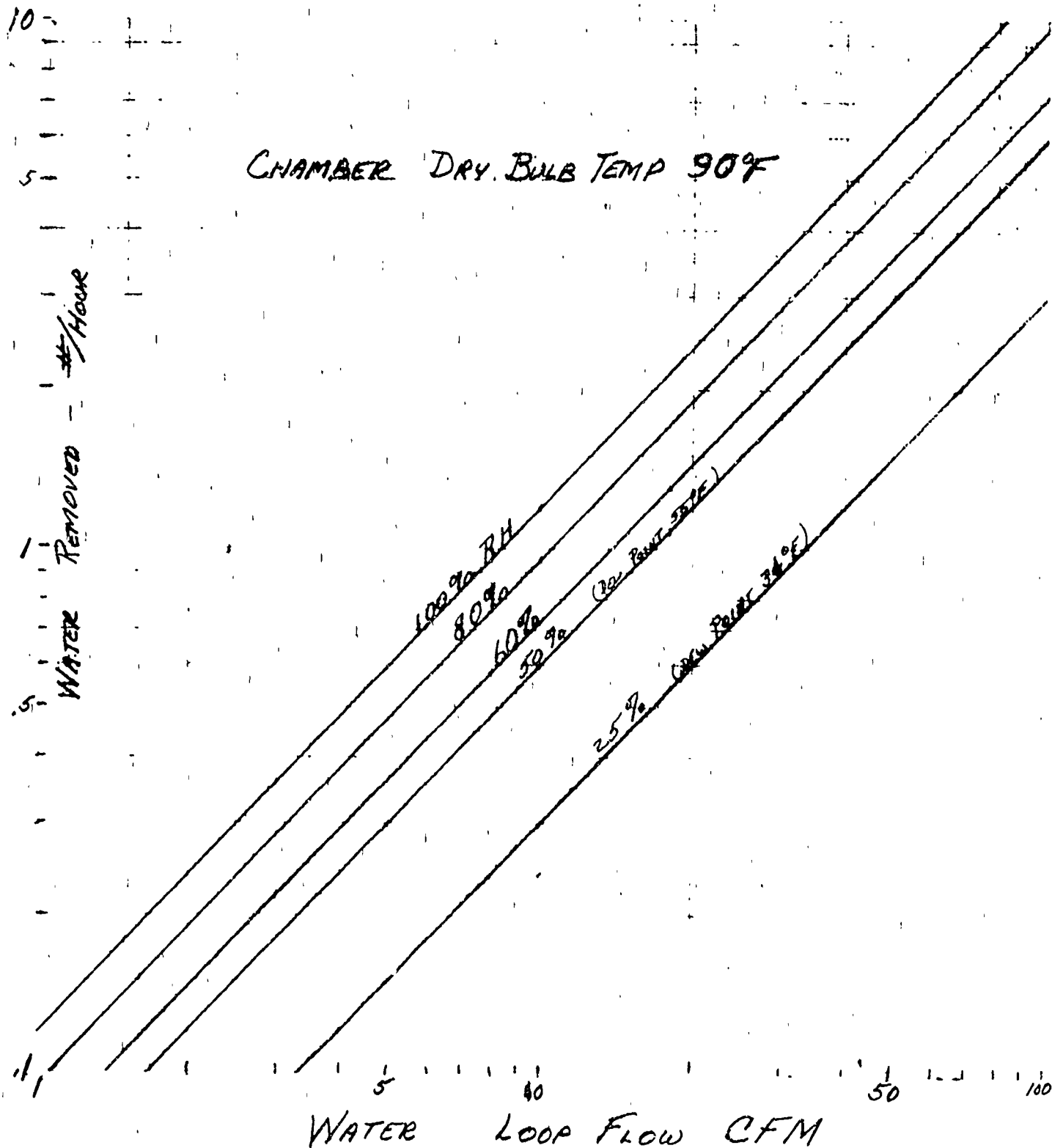
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condensed water, if a heat exchanger is used, or by humidifying the dry gas when it returned to the chamber atmosphere (similar to commercial air conditioning).

In view of the very high convective loss in helium atmospheres at high pressures (see Ref. 5), relative humidity is no doubt much less important at these pressures than it is at one atmosphere of air.

When the wet compartment of the High Pressure Facility is being used, it is expected that the relative humidity will approach 100% due to splashing and large wet surface areas in the chamber. In non-use periods, the water/gas interface will be covered to minimize evaporation.

#### D. Temperature:

It is well known that the ambient temperature in a helium environment must be higher than in air to maintain a suitable comfort level (Ref. 5). For the purpose of this study a chamber temperature of 90°F was chosen. At very high pressures the temperature will no doubt approach body temperature (98°F) to maintain comfort. However, the results shown in the following sections can be easily adjusted if a different ambient temperature is desired.

In view of the considerable amount of heat required due to heat loss from the vessel walls to the environment, only the process loop heat requirements are considered here. General heating will be accomplished by other means such as heating coils at the chamber floor.

#### E. Trace Contaminants:

It is difficult to obtain a quantitative estimate of the type and amount of the various trace gases that will be present after prolonged exposure in a chamber. Several studies have been made (Ref. 6 and 7), however, the results for any particular chamber might be quite different, depending on the type of paint and other materials and equipment that might outgas.

Probably of greatest concern for manned occupancy is the CO level because of the physiological consequences. Again, except for some data in the Sea Lab II reports (see Ref. 8) little information is available.

Ammonia and methane might be of concern as well for animal experiments.

The control of CO will be through use of "hopcalite" in the dry side of the purification loop. In addition there is evidence that many of the trace contaminants will be removed by molecular sieves (Ref. 9).

Concentrated gas samples will be taken periodically to monitor the impurities. This will be done by passing some of the chamber gas through a liquid nitrogen trap. In this way all the gases with a freezing point above  $-320^{\circ}\text{F}$  will be concentrated for analysis. If the concentration of impurities becomes too high, it will be necessary to have a complete chamber purge, passing the gas through a cleanup system. The proposed method of accomplishing the cleanup is by returning the purified gas to the chamber in a large flexible bag which will expand within the chamber. This will permit more efficient cleaning by a one pass method rather than by dilution.

#### References:

1. "Space Station Life Support System", J. C. Cody, R. M. Byke and W. G. Nelson, ASME Paper 71-AV-13, SAE/ASME/AIAA Life Support and Environmental Control Conference July 12-14, 1971.
2. "Space Shuttle Orbiter Environmental Control and Life Support Systems", O. T. Stoll and B. B. Turner, ASME Paper 71-AV-15, SAE/ASME/AIAA Life Support and Environmental Control Conference July 12-14, 1971.
3. "Space Shuttle Environmental Control and Life Support System", W. Herralu and G. N. Kleiner, ASME Paper 71-AV-16, SAE/ASME/AIAA Life Support and Environmental Control Conference July 12-14, 1971.
4. "Project Tektite I", D. C. Paul<sup>1</sup> and H. A. Cole, ONR Report DR 153, Supt. of Documents, U. S. Government Print Office, Washington, D.C. 20402.
5. "Body Heat Loss in Undersea Gaseous Environments", P. Webb Aerospace Medicine Vol. 41, No. 11, Nov. 1970, pp 1282-1288.
6. "Activated Charcoal Air Filter System for the NASA 1973 Basic Subsystem Module", A. J. Robell, R. P. Merrill and C. R. Arnold, Material Sciences Laboratory Report #6-78-68-21, Lockheed Palo Alto Research Laboratory, Palo Alto, Calif. 94304.
7. "Analysis of Trace Contaminants", P.P. Mader, A. S. Lucero, and E. P. Honorof, ASME Paper 71-AV-17, SAE/ASME/AIAA Life Support and Environmental Control Conference July 12-14, 1971.
8. "An Experimental 45-Day Undersea Saturation Dive at 205 Feet", D. C. Pauli and G. P. Clapper, ONR Report ACR-124, Supt. of Documents, U. S. Govy Printing Office, Washington, DC 20402.
9. Personal communication G. D. Hopson - NASA Marshall Space Flight Center, Huntsville, Alabama.

## II. Properties of Gases

### A. Assumptions

It was assumed that the perfect gas laws apply in the analysis of methods for removing CO<sub>2</sub> and water. Although the gases deviate from the ideal state at high pressures, this assumption was made to permit a more complete analytic solution. The accuracy is considered sufficient for this study.

Thermal conductivity, specific heat and viscosity were assumed to be temperature dependent but invariant with pressure. While this would not be sufficiently accurate for oxygen, water or carbon dioxide alone, the assumption is considered justified because, at high pressures helium is the predominant gas. Helium has a very low critical temperature and critical pressure and for the pressure ranges considered this is a valid approximation (Ref. 1).

### B. Density:

The gas density for the helium-oxygen mixture was determined from the perfect gas laws assuming the mixture was composed of one half atmosphere of oxygen with the balance helium. Helium density at 85°F and one atmosphere is .010 #/cu. ft. and oxygen is .081 #/cu. ft. The density of the mixture at 85°F would be

$$\begin{aligned}\rho_M &= .01 (P-.5) + .081 (.5) \\ &= .01P + .0355 \text{ \#/cu. ft.}\end{aligned}$$

A curve of Density as a function of pressure is shown in Fig. II-1A.

### C. Specific Heat:

The specific heat was determined by the weight % of each gas multiplied by the corresponding specific heat for that gas:

$$\begin{aligned}C_M &= \frac{\rho_{O_2}}{\rho_M} C_{O_2} + \frac{\rho_{He}}{\rho_M} C_{He} \\ &= \frac{.0355 (.218)}{\rho_M} + \frac{.01 P}{\rho_M} (1.25) \\ &= \frac{1}{\rho_M} (.00776 + .0125P) \text{ BTU/\#}\end{aligned}$$

This is shown in Fig. II-1B.

### D. Viscosity and Thermal Conductivity:

The viscosity of oxygen is very close to that of helium over the temperature

II-2

FIG II-1 A  
DENSITY

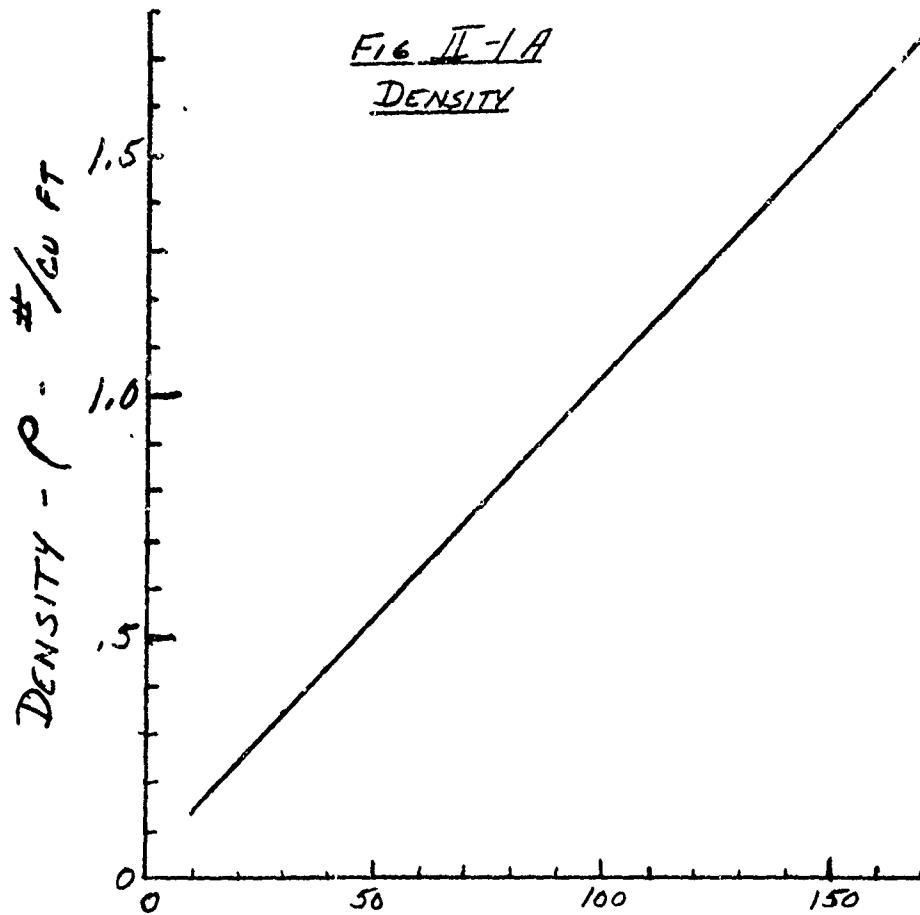


FIG II-1 B  
SPECIFIC HEAT

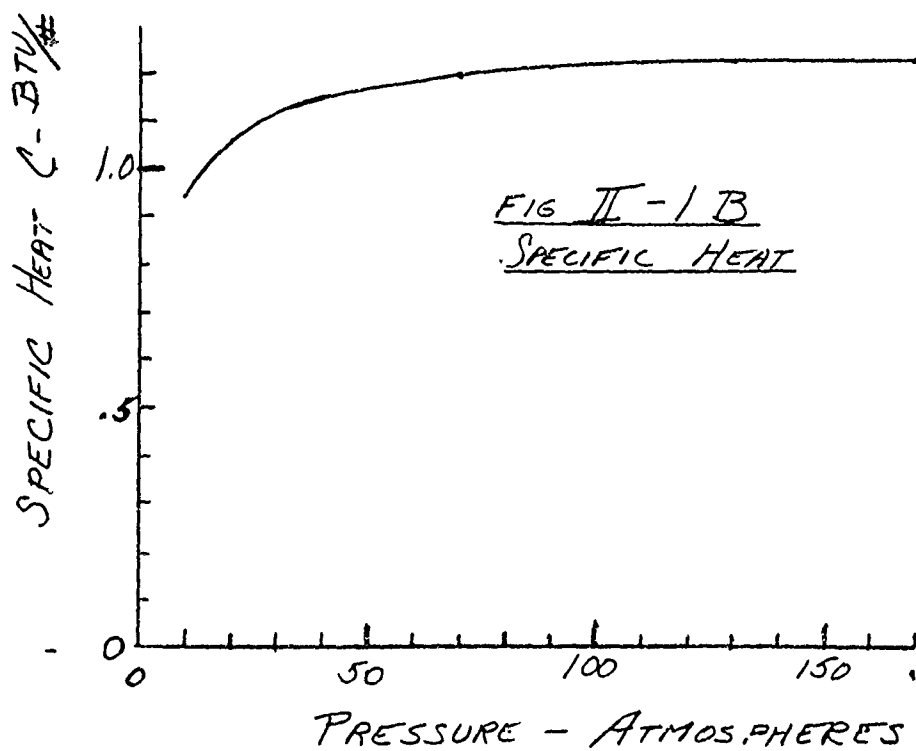


FIG II-1  
PROPERTIES HELIUM +  $\frac{1}{2}$  ATA OXYGEN

range of interest in this analysis. The viscosity value for helium was used (Reference 2) in the calculations.

The value for thermal conductivity was calculated on the basis that the Prandtl Number ( $cp/k$ ) is essentially constant. For oxygen and helium gases the Prandtl No. has a value of approximately 0.7.

### E. Diffusivity:

The diffusivity values for the gases were calculated using the relationship proposed by Wilke and Lee. For a more complete description and a tabular listing of constants for a number of gases the reader is referred to Reference 3 and 4 or to Reference 1, Section 14, pages 17 through 21.

Diffusivities for the gases of interest are given in Table II-1. Values for a background of air and of hydrogen are also given for reference purposes:

Table II-1  
Diffusivity of Pairs of Gases  
 $\text{cm}^2/\text{Sec} @ 1 \text{ ATA}$

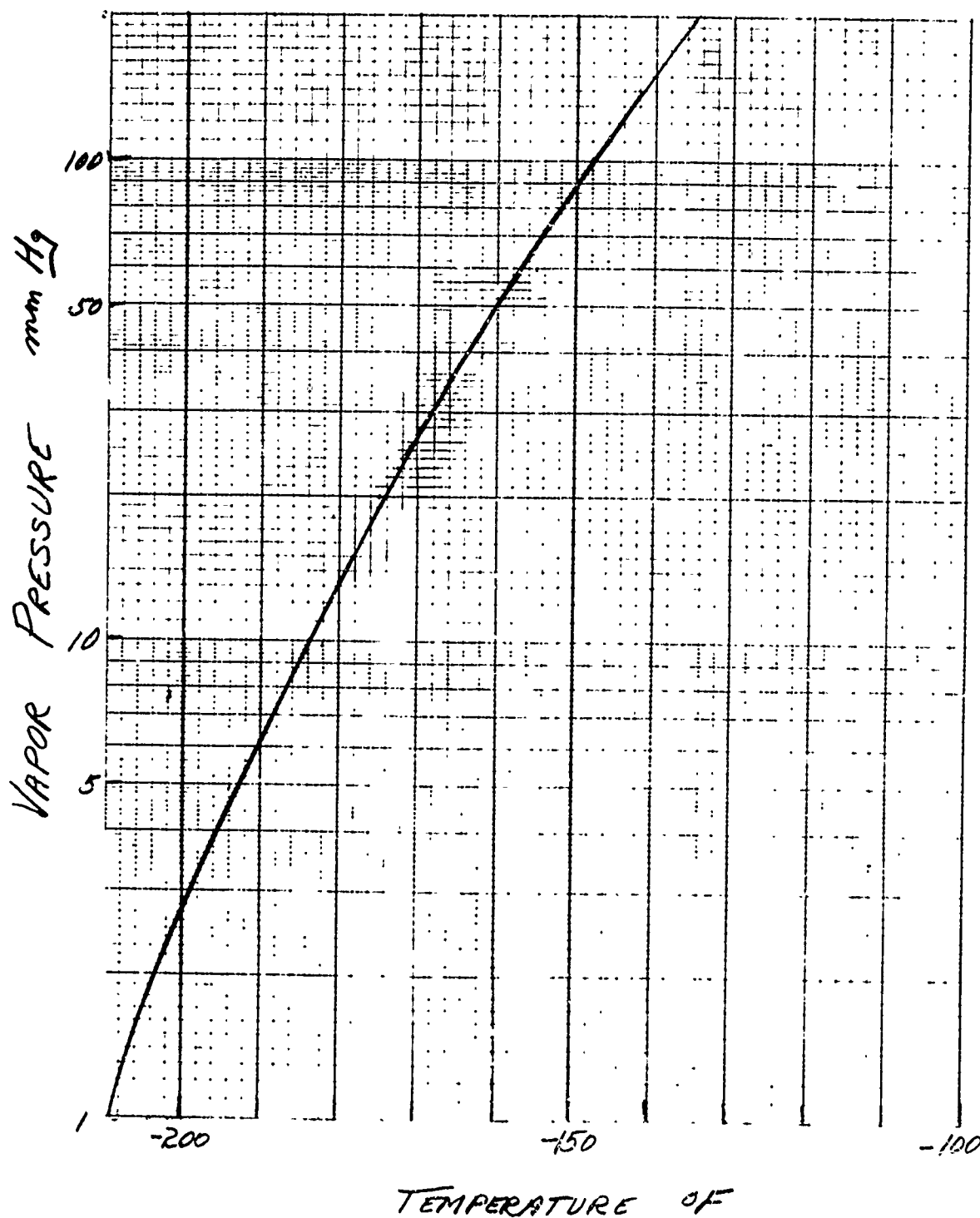
| Gas            | Helium |      |        | Hydrogen |      |        | Air  |      |        |
|----------------|--------|------|--------|----------|------|--------|------|------|--------|
|                | 85°F   | 32°F | -190°F | 85°F     | 32°F | -190°F | 85°F | 32°F | -190°F |
| Carbon Dioxide | .600   | .504 | .185   | .616     | .513 | .178   | .167 | .139 | .045   |
| Water          | .936   | .779 | .284   | .894     | .739 | .246   | .270 | .225 | .069   |
| Oxygen         | .744   | .635 | .237   | .778     | .694 | .223   | .225 | .186 | .063   |
| Methane        | .676   | .572 | .212   | .682     | .571 | .200   |      |      |        |

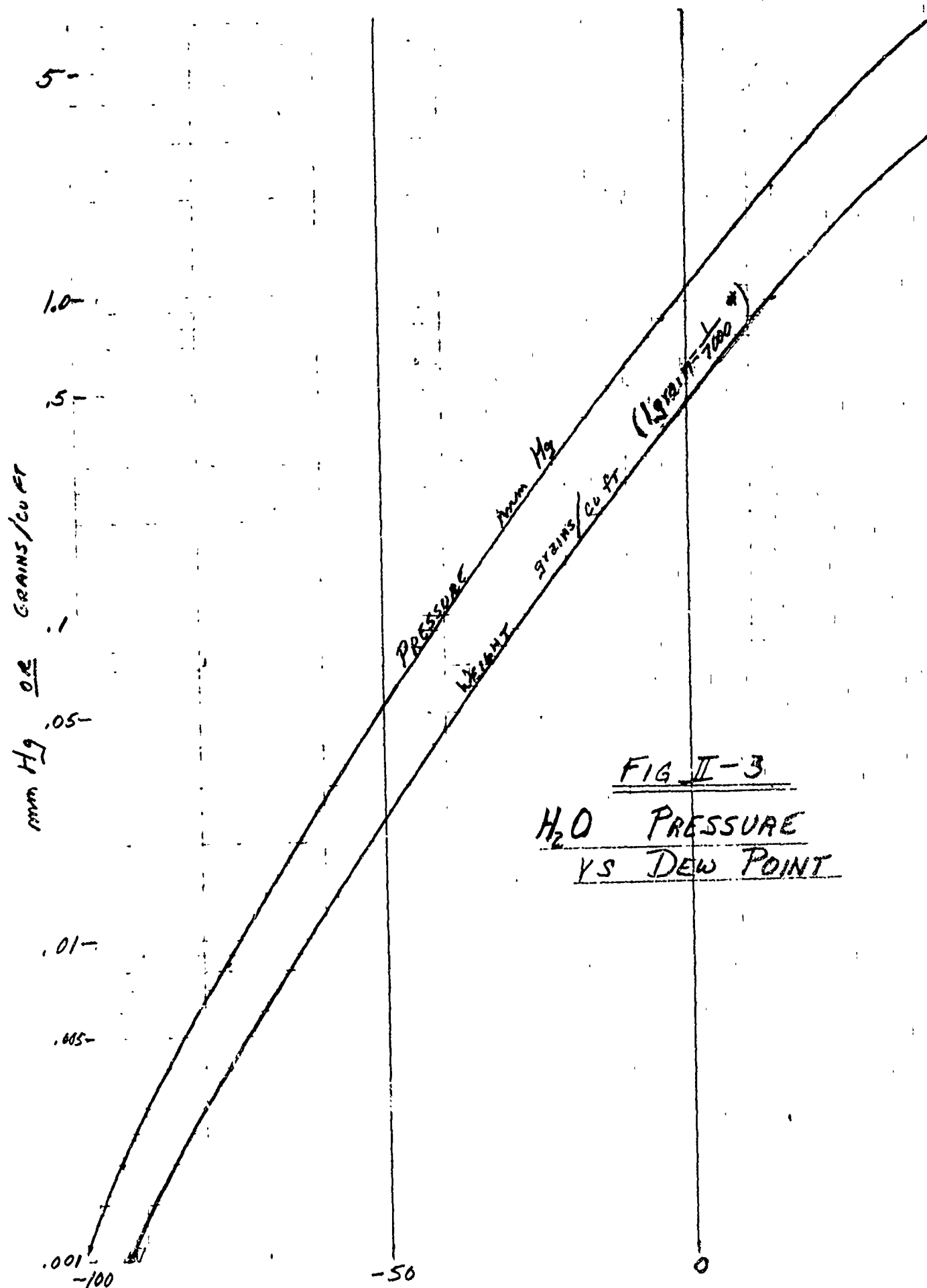
Diffusivity is inversely proportional to pressure, therefore at maximum chamber pressure the above values would be divided by 170. This is evident in the section on adsorption (Chapter IV) where, at high pressures, low diffusion of the gases reduces the adsorption efficiency appreciably. This will also pertain to removal of  $\text{CO}_2$  by chemical means (hydroxides or peroxides). In view of this, special care should be used in the design of life support systems at high pressure to assure adequate contact time between the gas and adsorbent (or chemical).

### F. Vapor Pressure of $\text{CO}_2$ and Water:

Figure II-2 is a curve of  $\text{CO}_2$  vapor pressure vs. temperature. It is necessary to cool the gas to below  $-190^\circ\text{F}$  in order to start freezing out  $\text{CO}_2$  for the low partial pressures desired.

Figure II-3 shows the vapor pressure of water vs. temperature for the low temperature region. A second curve on this figure gives the weight of water in grains per cubic foot vs. temperature.

DATA - FERRY'S - CHEM ENG - 4<sup>th</sup> EDFIG II - 2VAPOR PRESSURE - CO<sub>2</sub>





References:

1. "Chemical Engineers Handbook", R. H. Perry, C. H. Chilton, S. D. Kirkpatrick, Fourth Edition, Section 3.
2. "Compact Heat Exchangers", W. Kays and A. L. London. Second Edition, Appendix A.
3. Wilke and Lee, Industrial and Engineering Chemistry, Vol. 47, p. 1253 (1955).
4. Hirschfelder, Bird and Spotz, Trans. Am. Soc. of Mech. Engrs., Vol. 71, p. 921 (1949).

### III. Heat Exchangers

#### A. General:

Helium, having the lowest boiling point of the elements, can be purified by lowering the temperature and condensing the unwanted contaminants. Most of the major impurities, water and  $\text{CO}_2$ , can be removed at temperatures about  $100^\circ\text{F}$  warmer than the normal boiling point of oxygen ( $297^\circ\text{F}$ ) and about  $25^\circ\text{F}$  warmer than the normal boiling point of helium ( $-452^\circ\text{F}$ ).

A counter-current heat exchanger is one in which the gas is cooled to the low temperature required in one passage and then returned to the same heat exchanger in an adjacent passage to be warmed by the incoming gas. These are used to make the process more efficient since it is necessary to only provide the refrigeration for a driving force ( $\Delta T$ ) across the heat exchanger and to make up for heat transfer from the warm ambient gas to the cold surfaces of the heat exchanger. This is shown schematically in Fig. III-1.

If material is removed (e.g. water and  $\text{CO}_2$  condensed out of the gas stream) it is necessary to provide additional refrigeration to account for this in the system heat balance. In this case, however, with high pressure helium and a low percentage of contaminants the heat capacity of the gas requires the major part of the refrigeration and latent heat of the contaminants can be neglected as a first approximation.

#### B. Compact Heat Exchangers:

Heat transfer by convection can be estimated by the use of a coefficient (h)(Ref 1) in the simplified expression:

$$Q = h A \Delta t$$

Where:

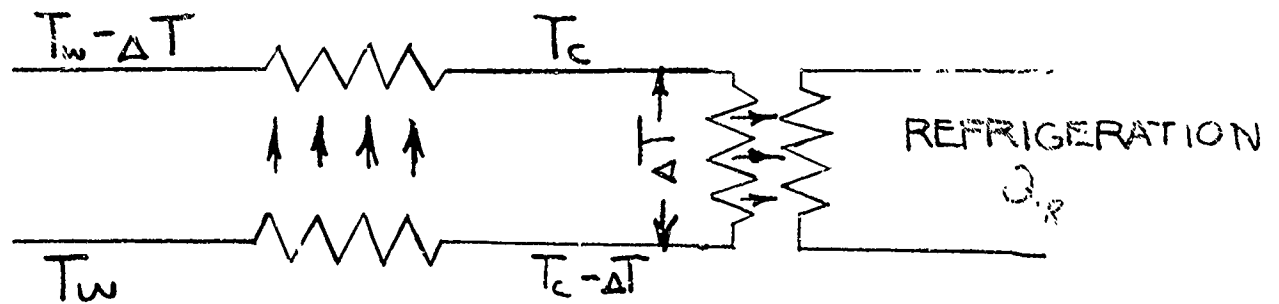
$Q$  = heat transfer rate, BTU/hr.

$h$  = overall coefficient, BTU/ $\text{Ft}^2\text{Hr}^\circ\text{F}$

$A$  = Surface area,  $\text{Ft}^2$

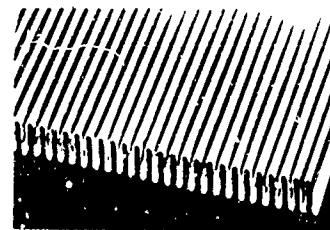
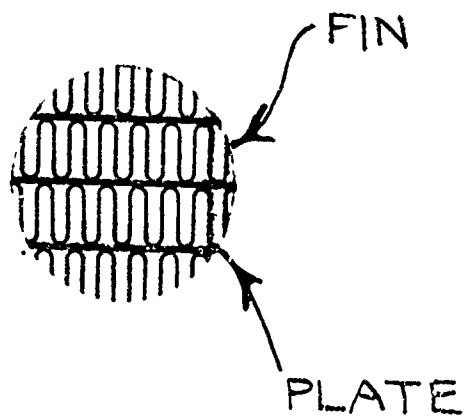
$\Delta t$  = Temperature difference,  $^\circ\text{F}$

The quantity of heat can be increased by increasing the area, the film coefficient or the temperature difference. There are many styles of commercial heat exchangers which have very large surface area per unit of volume (Ref. 2). However, the brazed aluminum plate - fin type is probably the most efficient. These have alternate layers of corrugated aluminum passages separated by a flat sheet (Figure III-2) similar to many layers of corrugated cardboard. The very high thermal conductivity

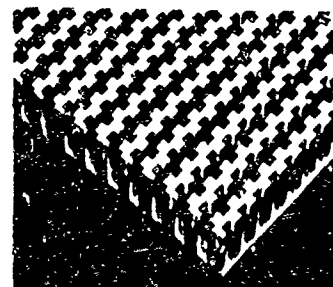


COUNTER CURRENT HEAT EXCHANGER

FIG III-1



STRAIGHT FIN



SERRATED FIN

FIG III-2

of aluminum assures that the temperature on the thin fin is essentially the same as the flat plate. Plate - fin heat exchangers of this type typically have surface areas of 350 to 500 sq. ft. per cubic foot of heat exchanger.

The film coefficient for gas can be increased appreciably by using a serrated fin (see Fig. III-2). The fin has notches, typically every 1/8 inch, along the flow. This interrupts the boundary layer and creates turbulence around the surface enhancing the heat transfer. This additional turbulence is accompanied by a higher pressure drop.

### C. Heat Transfer and Pressure Drop:

Figure III-3-A shows the correlation between the heat transfer coefficient and the mass flow rate for two typical compact heat exchangers (see Ref. 2 for other exchangers). A curve showing the correlation between mass rate and friction factor is shown in Fig. III-3-B. Characteristic geometry dimensions of these two heat exchangers are given below:

Table III-1  
Braze Aluminum Heat Exchangers  
(Ref 3)

| Style | Fin Type       | Fin              |                     | Spacing<br>Fins/In. | Free Flow<br>Area<br>% | Heat<br>Transfer<br>Ft <sup>2</sup> /Ft <sup>3</sup> |
|-------|----------------|------------------|---------------------|---------------------|------------------------|--|
|       |                | Height<br>Inches | Thickness<br>Inches |                     |                        |  |
| A     | Serrated(1/8") | .375             | .006                | 15                  | 88                     | 410  |
| B     | Straight       | .310             | .006                | 12.5                | 90                     | 365  |

Symbols used in Fig. III-3 and in the calculations are:

$G$  = Mass velocity, lb/hr.ft.<sup>2</sup>

$c$  = Specific heat, BTU/#

$h$  = Film coefficient, BTU/hr.ft<sup>2</sup> °F

$k$  = Thermal conductivity, BTU/hr. ft. °F

$\rho_1$  = Entering density, lb/cu.ft.

$\rho_2$  = Exit density, lb./cu.ft.

$\mu$  = Viscosity, lb/ft.hr.

$g$  = Gravity constant,  $4.17 \times 10^8$  ft/hr<sup>2</sup>

$\Delta P$  = Pressure drop, lb/ft.<sup>2</sup>

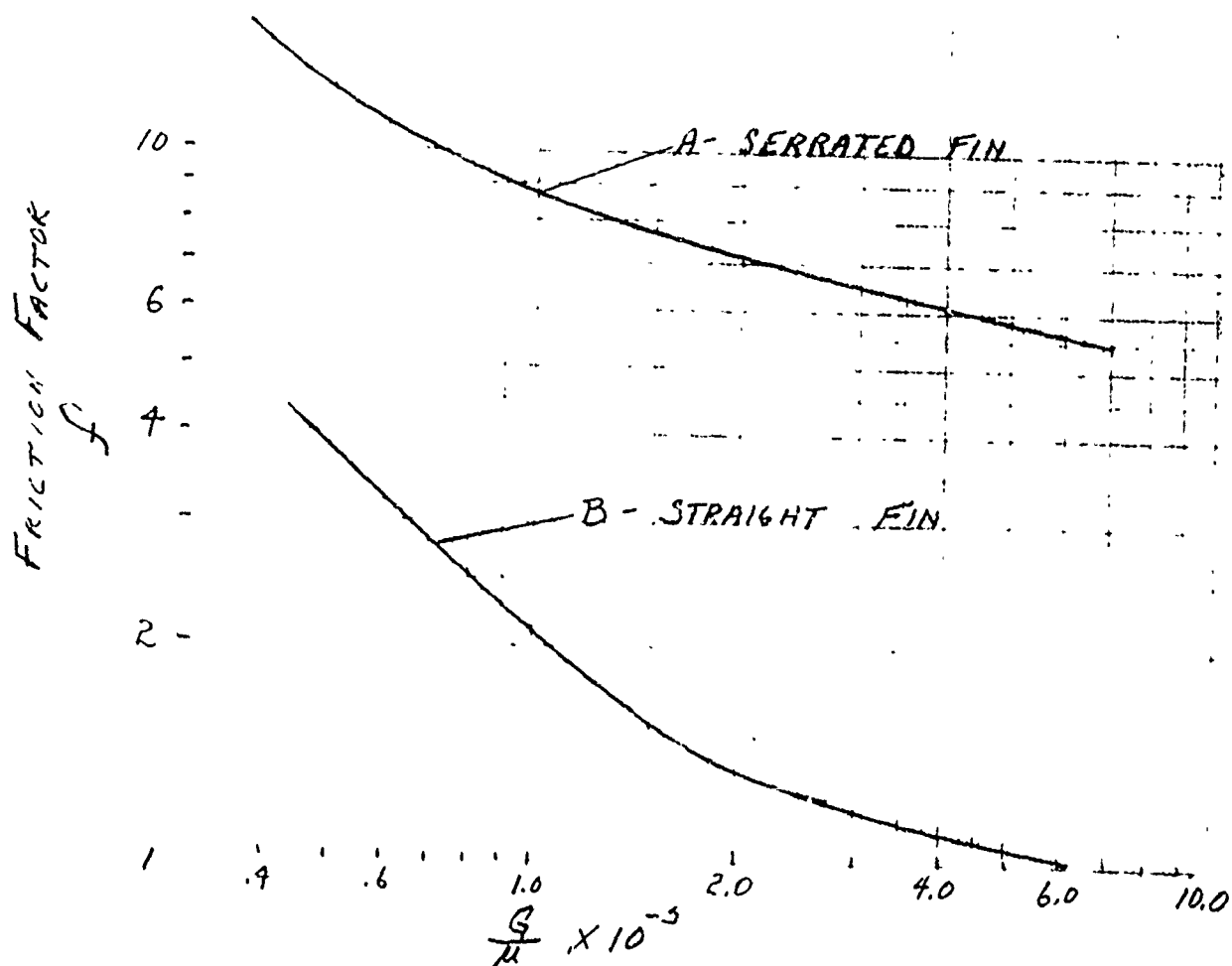
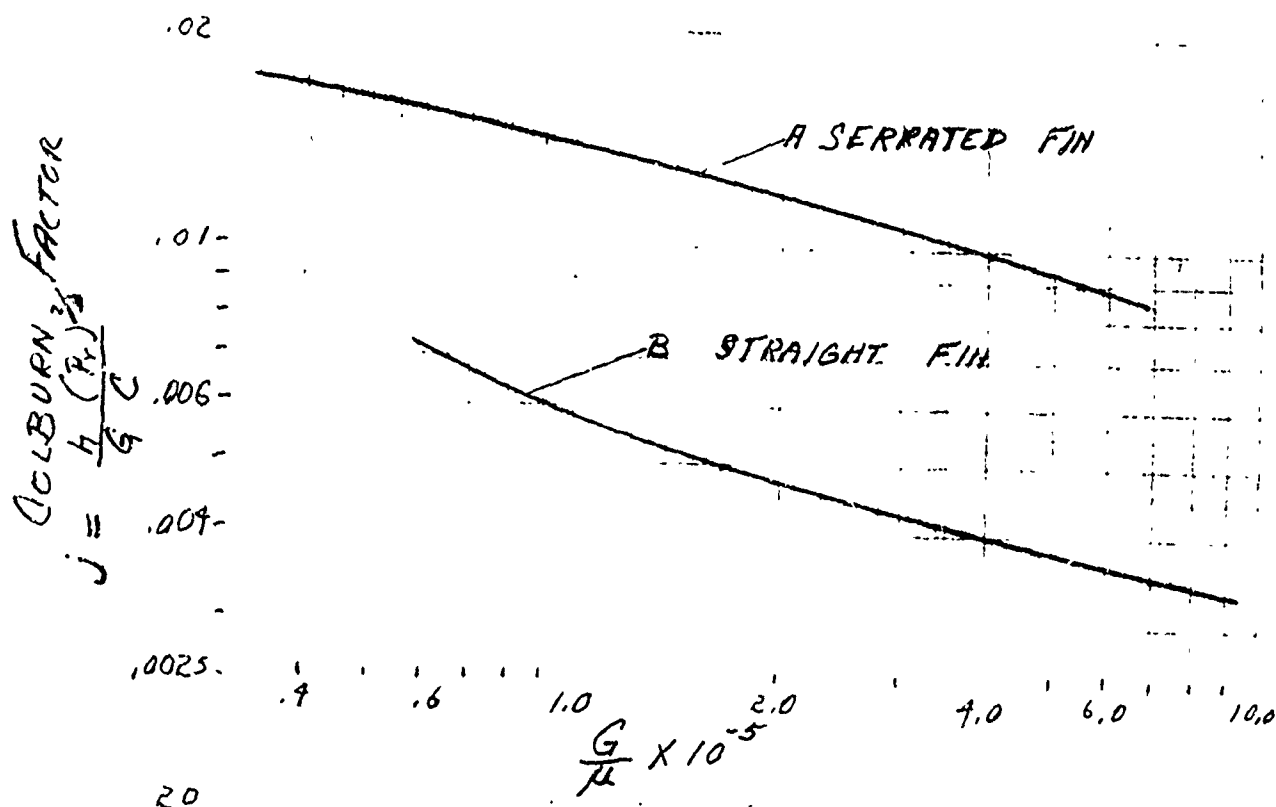


FIG III - 3 (REF. 3)  
HEAT TRANSFER & FLOW FRICTION

$L$  = Heat exchanger length, ft.

$f$  = Fanning friction factor, dimensionless

$j$  = Colburn factor, dimensionless

$Pr$  = Prandtl number, dimensionless =  $C_p \mu / k$

The film coefficient can be determined by assuming a mass velocity and evaluating the gas properties for the average temperature. This will permit obtaining the Colburn factor ( $j$ ) from curves on Fig. III-3-A. The film coefficient is the only unknown and can be calculated by:

$$h = j G C_p / (Pr)^{2/3}$$

The friction factor  $f$  can be found from the curves in Figure III-3-B using the same mass velocity. The pressure drop per foot can be calculated from:

$$\Delta P = \frac{f^2}{2g} \left[ \frac{8 FL}{\rho_1 + \rho_2} - \frac{.364}{\rho_1} + \frac{1.507}{\rho_2} \right]$$

Heat exchanger length and total pressure drop curves for two fin styles are plotted on Figures III-4 and III-5. Figure III-5 is for low temperature (-190°F CO<sub>2</sub> removal) with a heat exchanger temperature difference (between passages) of 10°F. Figure III-4 is for a heat exchanger cooling to 30°F (dehumidification) with a temperature difference between passages of 30°F. In both cases the gas is Helium + 1/2 ATA oxygen with a chamber temperature of 90°F. The curves are plotted for a velocity of 2 ft/sec. Values for other gas velocities are tabulated in the computer print outs appended to this section.

#### References:

1. "Heat Transmission" W. McAdams, McGraw Hill Book Company.
2. "Compact Heat Exchangers" 2nd Edition, W. Kays and A. L. London, McGraw Hill Book Co.
3. "Brazed Aluminum Heat Transfer Surface" Engineering Bulletin, The Trane Co., LaCrosse, Wisconsin.

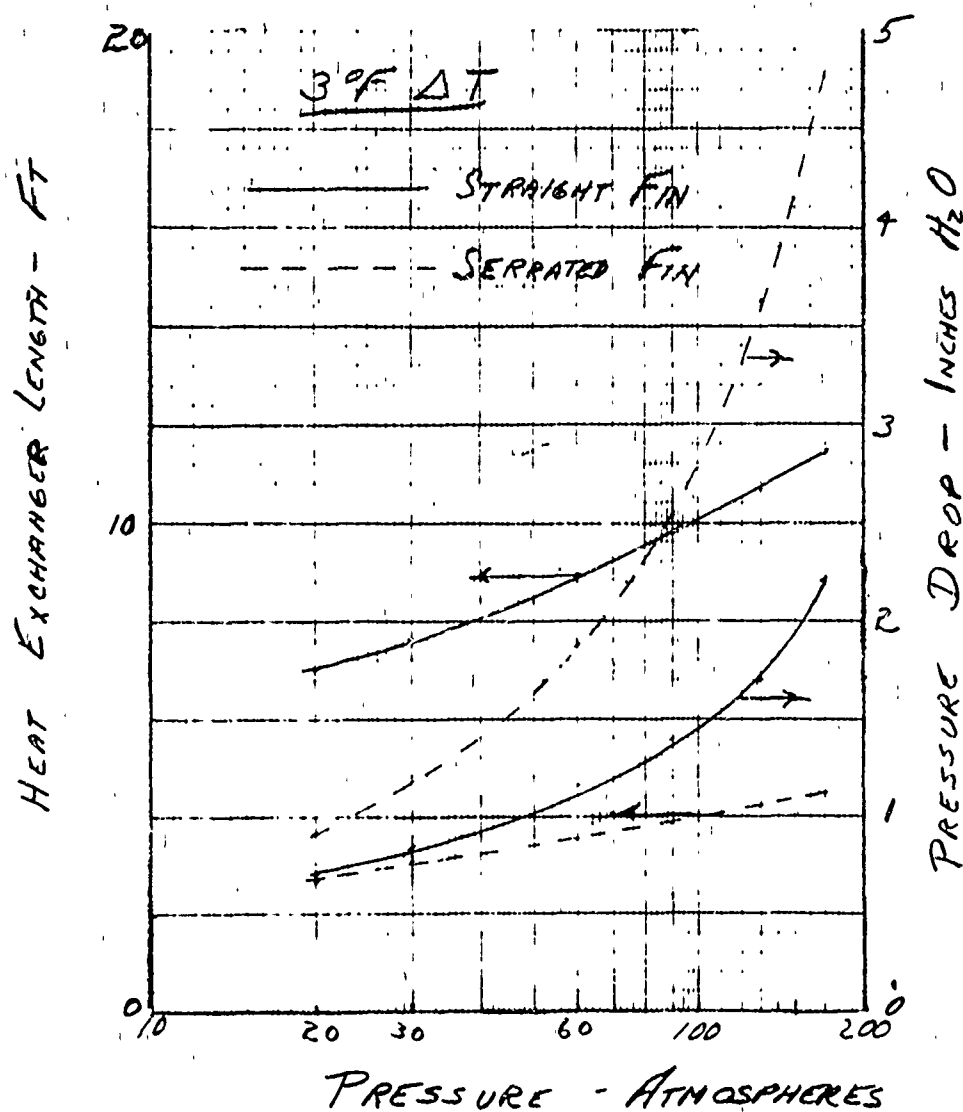
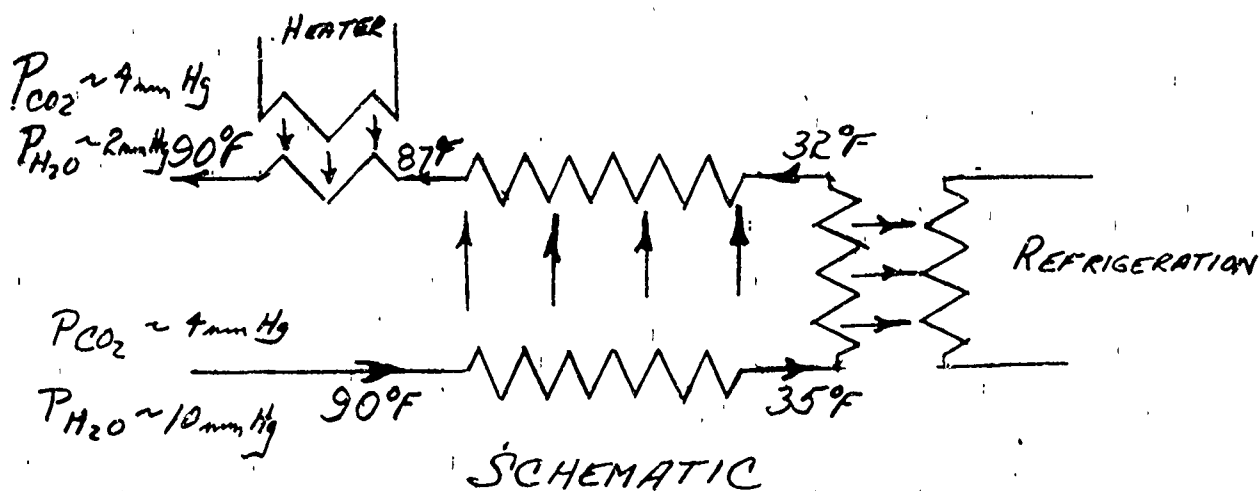
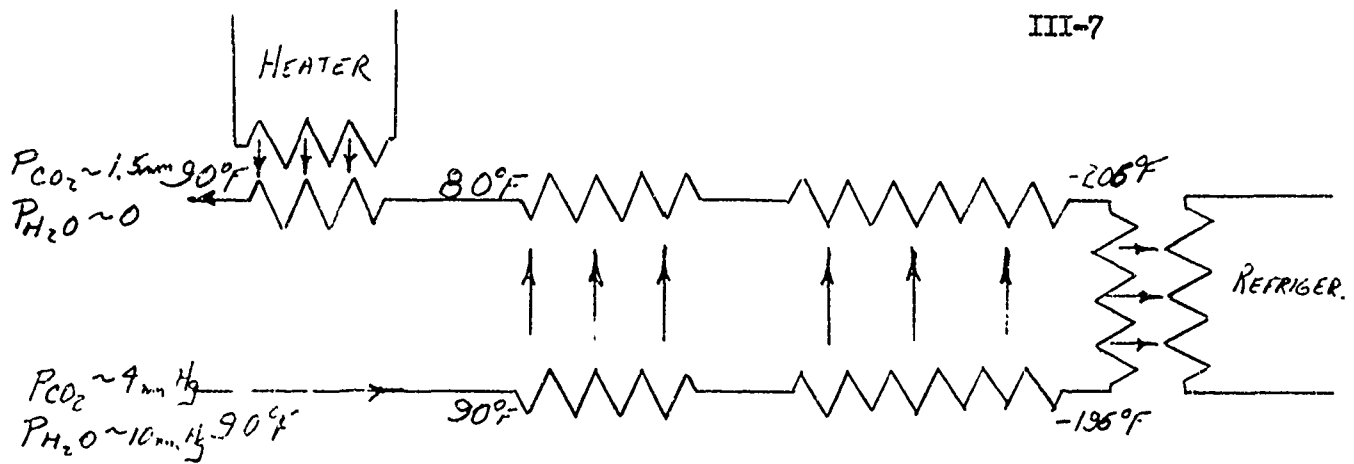
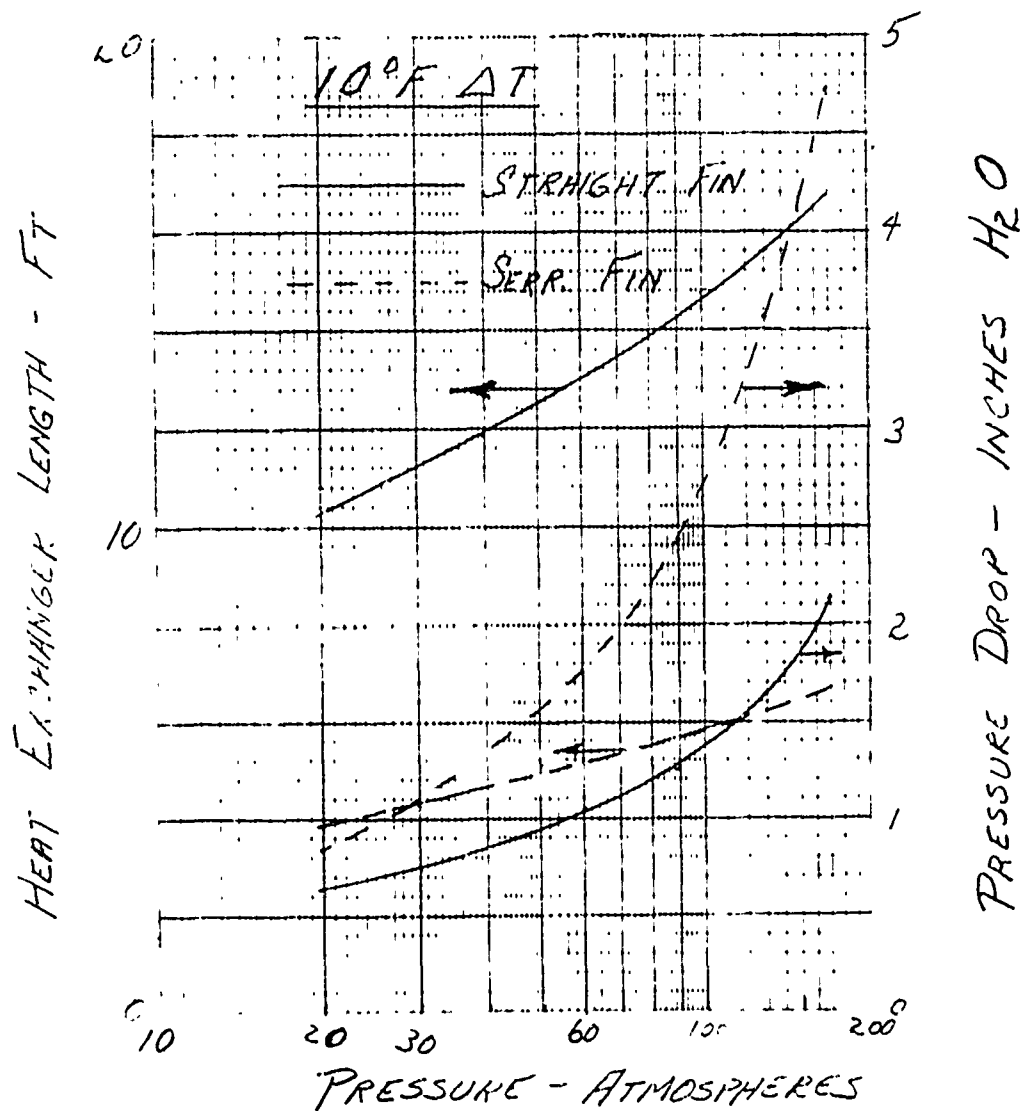


FIG III-4

LOW TEMPERATURE - DEHUMIDIFICATION



SCHEMATIC

FIG III - 5LOW TEMPERATURE -  $CO_2$  REMOVAL



III-APPENDIX  
Heat Exchanger Calculations

The following pages contain computer printouts for film coefficient  $h$ , length  $l$ , friction factor  $f$  and pressure drop for the two plate and fin heat exchangers described in Table III-1 and Figure III-3. These are arranged as follows (gas is helium + 1/2 ATA Oxygen):

- Appendix III-A - Serrated Fin - cooling from 90°F to -190°F,  
10°F temperature difference
- Appendix III-B - Straight Fin - cooling from 90°F to -190°F,  
10°F temperature difference
- Appendix III-C - Serrated Fin - cooling from 90°F to 30°F,  
30°F temperature difference
- Appendix III-D - Straight Fin - cooling from 90°F to 30°F,  
30°F temperature difference

To adjust the calculations for other temperature differences multiply the length and the pressure drop (for the desired velocity) by the ratio of  $t/10$  for Appendices A & B and by  $t/3$  for Appendices C & D.

III-9  
Appendix III-A  
90°F-190°F  
Serrated Fin

10 ATMOSPHERES

DENSITY AT AMB. TEMP. IS  
HEAT CAPACITY IS

.135  
.94777778

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 4                  | 31.407501                             | 4.1408452      | 13.196832         | 1.8639262                             |
| 6                  | 42.569821                             | 4.5825985      | 10.775168         | 3.7892076                             |
| 8                  | 52.82091                              | 4.9243226      | 9.3315695         | 6.2684509                             |
| 10                 | 62.443666                             | 5.2068372      | 8.3464095         | 9.2624774                             |
| 12                 | 71.59362                              | 5.4496588      | 7.6191946         | 12.743019                             |
| 14                 | 80.368232                             | 5.6637752      | 7.3092069         | 17.292681                             |
| 16                 | 88.833828                             | 5.8560394      | 7.1451545         | 22.829208                             |
| 18                 | 97.038208                             | 6.0310388      | 7.003509          | 29.167062                             |
| 20                 | 105.01731                             | 6.1920078      | 6.8791839         | 36.313853                             |
| 22                 | 112.79904                             | 6.34132        | 6.7686205         | 44.276448                             |
| 24                 | 120.40564                             | 6.480773       | 6.6692364         | 53.061105                             |
| 26                 | 127.8552                              | 6.6117639      | 6.579101          | 62.67358                              |
| 28                 | 135.16272                             | 6.7354017      | 6.496735          | 73.1192                               |
| 30                 | 142.34078                             | 6.8525831      | 6.4209813         | 84.402998                             |
| 32                 | 149.4001                              | 6.9640438      | 6.3509183         | 96.529411                             |
| 34                 | 156.34989                             | 7.0703958      | 6.2858007         | 109.50302                             |
| 36                 | 163.19816                             | 7.1721543      | 6.2250178         | 123.32788                             |
| 38                 | 169.95192                             | 7.269757       | 6.1680631         | 138.00789                             |
| 40                 | 176.61736                             | 7.3635798      | 6.1145123         | 153.54677                             |

30 ATMOSPHERES

DENSITY AT AMB. TEMP. IS  
HEAT CAPACITY IS

.335  
1.128209

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 43.951853                             | 4.3462741      | 11.847567         | 1.089543                              |
| 4                  | 73.917911                             | 5.1686201      | 8.3774949         | 3.6641358                             |
| 6                  | 100.18856                             | 5.7200184      | 7.233116          | 7.8770954                             |
| 8                  | 124.31461                             | 6.1465598      | 6.8878843         | 14.330124                             |
| 10                 | 146.96188                             | 6.4991957      | 6.6314904         | 22.794567                             |
| 12                 | 168.4964                              | 6.8022866      | 6.4291022         | 33.306977                             |
| 14                 | 189.14755                             | 7.0695476      | 6.262812          | 45.897633                             |
| 16                 | 209.07142                             | 7.3095327      | 6.1222456         | 60.592442                             |
| 18                 | 228.38053                             | 7.5279676      | 6.0008783         | 77.414088                             |
| 20                 | 247.15943                             | 7.7288898      | 5.8943517         | 96.382767                             |
| 22                 | 265.47382                             | 7.9152618      | 5.7996166         | 117.5167                              |
| 24                 | 283.37604                             | 8.0893276      | 5.7144605         | 140.8325                              |
| 26                 | 300.90867                             | 8.252831       | 5.637229          | 166.34544                             |
| 28                 | 318.10699                             | 8.4071563      | 5.5666546         | 194.06966                             |
| 30                 | 335.00064                             | 8.5534226      | 5.5017459         | 224.01834                             |
| 32                 | 351.61482                             | 8.6925482      | 5.4417132         | 256.20379                             |

III-10  
Appendix III-A  
90°F-190°F  
Serrated Fin

60 ATMOSPHERES

DENSITY AT AMB. TEMP. IS  
HEAT CAPACITY IS

.635  
1.185748

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 74.623694                             | 5.0925755      | 8.6052742         | 1.7573552                             |
| 4                  | 125.50159                             | 6.0561271      | 6.9509958         | 6.7521201                             |
| 6                  | 170.10524                             | 6.7022063      | 6.4880101         | 15.693706                             |
| 8                  | 211.06768                             | 7.2019894      | 6.1783418         | 28.550178                             |
| 10                 | 249.51936                             | 7.6151766      | 5.9483598         | 45.414004                             |
| 12                 | 286.08177                             | 7.9703114      | 5.7668203         | 66.358008                             |
| 14                 | 321.14434                             | 8.283464       | 5.6176601         | 91.442508                             |
| 16                 | 354.97211                             | 8.564657       | 5.4915739         | 120.71912                             |

90 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.935  
1.2063636

LBS/CU FT.  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 35.879468                             | 3.9640490      | 14.18325          | .20757784                             |
| 1                  | 60.341832                             | 4.7150276      | 10.029072         | .69809498                             |
| 1.5                | 81.7875                               | 5.2100350      | 8.1887033         | 1.4191489                             |
| 2                  | 101.48246                             | 5.6071443      | 7.3224377         | 2.4241593                             |
| 2.5                | 119.97023                             | 5.9288333      | 7.049868          | 3.8560514                             |
| 3                  | 137.54963                             | 6.2053253      | 6.8347113         | 5.6343901                             |
| 3.5                | 154.4679                              | 6.4491317      | 6.6579299         | 7.7642973                             |
| 4                  | 170.67247                             | 6.668056       | 6.5084952         | 10.250156                             |
| 4.5                | 186.43518                             | 6.8673213      | 6.3794709         | 13.095804                             |
| 5                  | 201.78507                             | 7.0506108      | 6.2662236         | 16.304657                             |
| 5.5                | 216.71576                             | 7.220627       | 6.1655117         | 19.879798                             |
| 6                  | 231.32998                             | 7.379417       | 6.0749831         | 23.824038                             |
| 6.5                | 245.6425                              | 7.5285715      | 5.9928701         | 28.13996                              |
| 7                  | 259.6821                              | 7.6693534      | 5.9178523         | 32.829956                             |
| 7.5                | 273.47299                             | 7.8027834      | 5.8488405         | 37.896255                             |
| 8                  | 287.03574                             | 7.9296996      | 5.7850233         | 43.340942                             |
| 8.5                | 300.38807                             | 8.0507987      | 5.7257129         | 49.16598                              |
| 9                  | 313.54535                             | 8.1666673      | 5.670346          | 55.373221                             |
| 9.5                | 326.52106                             | 8.277804       | 5.6184662         | 61.964418                             |
| 10                 | 339.32705                             | 8.3846365      | 5.569687          | 68.941239                             |
| 10.5               | 351.9739                              | 8.4875347      | 5.5236812         | 76.30527                              |
| 11                 | 364.47102                             | 8.586821       | 5.48017           | 84.058029                             |
| 11.5               | 376.82687                             | 8.682778       | 5.4389135         | 92.200966                             |

130 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

1.335  
1.2194382

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 47.37288                              | 4.3327891      | 11.869733         | .27103325                             |
| 1                  | 79.67137                              | 5.1525836      | 8.3931685         | .91148526                             |
| 1.5                | 107.98681                             | 5.7022712      | 7.2377142         | 1.9570765                             |
| 2                  | 133.99074                             | 6.1274891      | 6.8922631         | 3.5603416                             |
| 2.5                | 158.40077                             | 6.4790309      | 6.6357061         | 5.6633458                             |
| 3                  | 181.61145                             | 6.7811814      | 6.4331893         | 8.275171                              |
| 3.5                | 203.87                                | 7.0476132      | 6.2667934         | 11.40334                              |
| 4                  | 225.34467                             | 7.2868537      | 6.1261376         | 15.054289                             |
| 4.5                | 246.15671                             | 7.5046109      | 6.0046931         | 19.233654                             |
| 5                  | 266.39728                             | 7.7049097      | 5.8980988         | 23.946453                             |
| 5.5                | 286.13719                             | 7.8907035      | 5.8033036         | 29.197210                             |
| 6                  | 305.43284                             | 8.0642292      | 5.7180932         | 34.990062                             |
| 6.5                | 324.33014                             | 8.2272253      | 5.6408126         | 41.328794                             |
| 7                  | 342.8671                              | 8.3810718      | 5.5701935         | 48.216922                             |
| 7.5                | 361.07568                             | 8.5268842      | 5.5052435         | 55.657719                             |
| 8                  | 378.98304                             | 8.6655782      | 5.4451726         | 63.654249                             |

170 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

1.735  
1.2264841

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 57.995673                             | 4.6254606      | 10.411944         | .32903144                             |
| 1                  | 97.536708                             | 5.5006306      | 7.4163096         | 1.1173487                             |
| 1.5                | 132.20155                             | 6.0874485      | 6.9223306         | 2.5970157                             |
| 2                  | 164.03654                             | 6.5413891      | 6.5919323         | 4.7245256                             |
| 2.5                | 193.92022                             | 6.9166768      | 6.346555          | 7.5151811                             |
| 3                  | 222.33561                             | 7.239237       | 6.1528629         | 10.981033                             |
| 3.5                | 249.58537                             | 7.5236657      | 5.9937177         | 15.132064                             |
| 4                  | 275.87547                             | 7.7790664      | 5.8591909         | 19.976815                             |
| 4.5                | 301.35436                             | 8.0115327      | 5.7430384         | 25.522764                             |
| 5                  | 326.13364                             | 8.2253613      | 5.641089          | 31.776571                             |
| 5.5                | 350.29998                             | 8.4237051      | 5.5504244         | 38.744242                             |
| 6                  | 373.92244                             | 8.6089522      | 5.4689271         | 46.431255                             |

III-12  
Appendix III-B  
90°F-190°F  
100 A T  
Straight Fin

10 ATMOSPHERES  $\frac{1}{2}$  17.7. 02

DENSITY AT AMB. TEMP. IS .135  
HEAT CAPACITY IS .94777778

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 4                  | 13.75511                              | 10.505478      | 3.7795969         | 1.3539112                             |
| 6                  | 18.643717                             | 11.626222      | 2.788541          | 2.486629                              |
| 8                  | 23.133245                             | 12.493189      | 2.2473617         | 3.8275532                             |
| 10                 | 27.347591                             | 13.209939      | 1.9010366         | 5.3481062                             |
| 12                 | 31.35487                              | 13.825986      | 1.6580764         | 7.0290059                             |
| 14                 | 35.197766                             | 14.369207      | 1.4770474         | 8.8560971                             |
| 16                 | 38.905326                             | 14.856989      | 1.3211451         | 10.695515                             |
| 18                 | 42.498485                             | 15.300969      | 1.2282102         | 13.536512                             |
| 20                 | 45.992982                             | 15.709353      | 1.2494619         | 16.711743                             |
| 22                 | 49.401039                             | 16.088164      | 1.2200422         | 20.221209                             |
| 24                 | 52.732396                             | 16.441961      | 1.1937894         | 24.06491                              |
| 26                 | 55.994979                             | 16.77429       | 1.1701383         | 28.242846                             |
| 28                 | 59.195351                             | 17.087964      | 1.1486587         | 32.755016                             |
| 30                 | 62.339026                             | 17.385257      | 1.1290163         | 37.601422                             |
| 32                 | 65.430699                             | 17.668037      | 1.1109462         | 42.782062                             |
| 34                 | 68.474404                             | 17.937856      | 1.0942355         | 48.296937                             |
| 36                 | 71.473648                             | 18.196021      | 1.0787105         | 54.146047                             |
| 38                 | 74.4315                               | 18.443643      | 1.0642279         | 60.329392                             |
| 40                 | 77.350668                             | 18.681675      | 1.0506681         | 66.846972                             |

30 ATMOSPHERES

DENSITY AT AMB. TEMP. IS .335  
HEAT CAPACITY IS 1.128209

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 19.248987                             | 11.026658      | 3.2150275         | .74980195                             |
| 4                  | 32.372808                             | 13.112981      | 1.9116668         | 2.1195903                             |
| 6                  | 43.878201                             | 14.511899      | 1.3451322         | 3.7117385                             |
| 8                  | 54.444356                             | 15.59405       | 1.2517865         | 6.5986463                             |
| 10                 | 64.362866                             | 16.4887        | 1.1838666         | 10.310385                             |
| 12                 | 73.794043                             | 17.257653      | 1.1311168         | 14.846954                             |
| 14                 | 82.838342                             | 17.935704      | 1.0883555         | 20.208354                             |
| 16                 | 91.564127                             | 18.544555      | 1.0526228         | 26.394585                             |
| 18                 | 100.02067                             | 19.098733      | 1.0220794         | 33.405647                             |
| 20                 | 108.24501                             | 19.60848       | .99550918         | 41.241539                             |
| 22                 | 116.26591                             | 20.081312      | .97206901         | 49.902263                             |
| 24                 | 124.10629                             | 20.522924      | .95115207         | 59.387817                             |
| 26                 | 131.78482                             | 20.937738      | .93230805         | 69.698201                             |
| 28                 | 139.31693                             | 21.329267      | .9151942          | 80.833417                             |
| 30                 | 146.71561                             | 21.70035       | .89954409         | 92.793464                             |
| 32                 | 153.99189                             | 22.053317      | .88514674         | 105.57834                             |

III-13  
Appendix III-B  
90°F-190°F  
10° Δ T  
Straight Fin

60 ATMOSPHERES

DENSITY AT AMB. TEMP. IS  
HEAT CAPACITY IS

.635  
1.185748

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 32.68191                              | 12.920053      | 1.9901601         | 1.0303388                             |
| 4                  | 54.964202                             | 15.364619      | 1.2686901         | 3.1225574                             |
| 6                  | 74.498644                             | 17.003746      | 1.1463909         | 7.0257541                             |
| 8                  | 92.4384                               | 18.271714      | 1.0668369         | 12.49023                              |
| 10                 | 109.27855                             | 19.319985      | 1.0089521         | 19.515984                             |
| 12                 | 125.29129                             | 20.220975      | .96399599         | 28.103017                             |
| 14                 | 140.64716                             | 21.015455      | .92755257         | 38.251328                             |
| 16                 | 155.46224                             | 21.728852      | .89709935         | 49.960918                             |

90 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.935  
1.2063636

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 15.713635                             | 10.058971      | 4.2111878         | .15632097                             |
| 1                  | 26.427079                             | 11.9622        | 2.5039871         | .44193838                             |
| 1.5                | 35.819343                             | 13.23835       | 1.8474115         | .81160497                             |
| 2                  | 44.444873                             | 14.225533      | 1.4880796         | 1.2491742                             |
| 2.5                | 52.841707                             | 15.04167       | 1.295017          | 1.7951578                             |
| 3                  | 60.240714                             | 15.74314       | 1.2376013         | 2.5050273                             |
| 3.5                | 67.623899                             | 16.361686      | 1.1908143         | 3.5105094                             |
| 4                  | 74.747068                             | 16.917105      | 1.1517178         | 4.5956041                             |
| 4.5                | 81.650445                             | 17.422648      | 1.118299          | 5.8163114                             |
| 5                  | 88.364266                             | 17.887661      | 1.0892274         | 7.1806313                             |
| 5.5                | 94.912014                             | 18.318998      | 1.0635806         | 8.6885639                             |
| 6                  | 101.3124                              | 18.721854      | 1.0406945         | 10.340109                             |
| 6.5                | 107.58066                             | 19.100265      | 1.0200765         | 12.135267                             |
| 7                  | 113.72939                             | 19.457434      | 1.0013515         | 14.074037                             |
| 7.5                | 119.76919                             | 19.795951      | .98422808         | 16.15642                              |
| 8                  | 125.70908                             | 20.117942      | .96847535         | 18.382446                             |
| 8.5                | 131.55682                             | 20.425175      | .95390766         | 20.752025                             |
| 9                  | 137.31913                             | 20.719137      | .94037363         | 23.265246                             |
| 9.5                | 143.00192                             | 21.001095      | .9277488          | 25.922079                             |
| 10                 | 148.61039                             | 21.272133      | .91592744         | 28.722525                             |
| 10.5               | 154.14915                             | 21.53319       | .90482323         | 31.666584                             |
| 11                 | 159.62234                             | 21.785083      | .89436109         | 34.754256                             |
| 11.5               | 165.03367                             | 22.028529      | .88447713         | 37.98554                              |

III-14  
Appendix III-B  
90°F-190°F  
100 Δ T  
Straight Fin

130 ATMOSPHERES

|                           |                                       |                |                   |                                       |
|---------------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| DENSITY AT AMB. TEMP. IS: | 1.335                                 | LBS/CU FT      |                   |                                       |
| HEAT CAPACITY IS:         | 1.2194382                             | BTU/LB         |                   |                                       |
| VELOCITY<br>FT/SEC        | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
| .5                        | 20.747247                             | 10.992446      | 3.2240543         | .18669426                             |
| 1                         | 34.892571                             | 13.072296      | 1.9170342         | .52775971                             |
| 1.5                       | 47.293496                             | 14.466873      | 1.3463899         | .92246073                             |
| 2                         | 58.682076                             | 15.545667      | 1.252957          | 1.6399302                             |
| 2.5                       | 69.372601                             | 16.437541      | 1.1849735         | 2.5623909                             |
| 3                         | 79.537862                             | 17.204108      | 1.1321744         | 3.6898429                             |
| 3.5                       | 89.286131                             | 17.880056      | 1.0893731         | 5.0222862                             |
| 4                         | 98.691094                             | 18.487018      | 1.053607          | 6.5597297                             |
| 4.5                       | 107.80586                             | 19.039476      | 1.0230351         | 8.3021465                             |
| 5                         | 116.67034                             | 19.547641      | .99644            | 10.249564                             |
| 5.5                       | 125.31556                             | 20.019007      | .97297791         | 12.401972                             |
| 6                         | 133.76621                             | 20.459248      | .95204142         | 14.759372                             |
| 6.5                       | 142.0424                              | 20.872775      | .93317977         | 17.321763                             |
| 7                         | 150.16077                             | 21.26309       | .91604993         | 20.089145                             |
| 7.5                       | 158.13533                             | 21.633021      | .90038518         | 23.061518                             |
| 8                         | 165.97797                             | 21.984893      | .88597437         | 26.238883                             |

170 ATMOSPHERES

|                           |                                       |                |                   |                                       |
|---------------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| DENSITY AT AMB. TEMP. IS: | 1.735                                 | LBS/CU FT      |                   |                                       |
| HEAT CAPACITY IS:         | 1.2264841                             | BTU/LB         |                   |                                       |
| VELOCITY<br>FT/SEC        | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
| .9                        | 25.399565                             | 11.734965      | 2.6487361         | .2127609                              |
| 1                         | 42.710806                             | 13.955304      | 1.5749479         | .60140002                             |
| 1.5                       | 57.898488                             | 15.444082      | 1.2610035         | 1.1986677                             |
| 2                         | 71.849813                             | 16.595746      | 1.173496          | 2.1309649                             |
| 2.5                       | 84.928564                             | 17.547865      | 1.109824          | 3.3296326                             |
| 3                         | 97.373261                             | 18.366212      | 1.0603733         | 4.7946709                             |
| 3.5                       | 109.30746                             | 19.087819      | 1.0202864         | 6.5260799                             |
| 4                         | 120.82137                             | 19.73578       | .98678855         | 8.5238594                             |
| 4.5                       | 131.98001                             | 20.325355      | .95815545         | 10.78801                              |
| 5                         | 142.83225                             | 20.868046      | .93324699         | 13.31853                              |
| 5.5                       | 153.41605                             | 21.371252      | .91127284         | 16.115422                             |
| 6                         | 163.76165                             | 21.84123       | .89166411         | 19.178684                             |

III-15  
Appendix III-C  
1/2 O<sub>2</sub>-Bal He  
900F-300F  
Serrated Fin

10 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.135  
.9477778

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 4                  | 32.699631                             | 2.9273725      | 14.305025         | 2.0518197                             |
| 6                  | 44.321178                             | 3.2396702      | 11.680004         | 4.1729093                             |
| 8                  | 54.994005                             | 3.4812522      | 10.11518          | 6.9054189                             |
| 10                 | 65.012648                             | 3.630976       | 9.0472923         | 10.206388                             |
| 12                 | 74.539039                             | 3.8526389      | 8.2590101         | 14.04482                              |
| 14                 | 83.674646                             | 4.0040086      | 7.6463576         | 18.39674                              |
| 16                 | 92.488523                             | 4.1399299      | 7.343753          | 23.061558                             |
| 18                 | 101.03044                             | 4.2636458      | 7.1981705         | 30.484502                             |
| 20                 | 109.33781                             | 4.3774429      | 7.0703898         | 37.952437                             |
| 22                 | 117.43968                             | 4.4829992      | 6.9567533         | 46.272501                             |
| 24                 | 125.35922                             | 4.5815856      | 6.8546068         | 55.451202                             |
| 26                 | 133.11527                             | 4.6741896      | 6.7619661         | 65.494532                             |
| 28                 | 140.72342                             | 4.7615955      | 6.6773108         | 76.408003                             |
| 30                 | 148.19679                             | 4.8444369      | 6.5994515         | 88.196803                             |
| 32                 | 155.54653                             | 4.9232341      | 6.5274411         | 100.86573                             |
| 34                 | 162.78225                             | 4.9984197      | 6.4605135         | 114.4194                              |
| 36                 | 169.91227                             | 5.0703579      | 6.3980412         | 128.86203                             |
| 38                 | 176.94368                             | 5.1493582      | 6.3395035         | 144.1977                              |
| 40                 | 183.88354                             | 5.2256862      | 6.2844642         | 160.43027                             |

30 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.335  
1.128209

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 45.760067                             | 3.0127141      | 12.842457         | 1.1763532                             |
| 4                  | 76.958953                             | 3.5827411      | 9.0809881         | 3.9592137                             |
| 6                  | 104.3104                              | 3.9649547      | 7.4341594         | 8.0739899                             |
| 8                  | 129.42902                             | 4.2606212      | 7.079332          | 14.686503                             |
| 10                 | 153.00001                             | 4.5050084      | 6.8158116         | 23.359256                             |
| 12                 | 175.42848                             | 4.7151524      | 6.6077902         | 34.129513                             |
| 14                 | 196.92923                             | 4.9004102      | 6.436886          | 47.028141                             |
| 16                 | 217.67279                             | 5.066761       | 6.2924125         | 62.081551                             |
| 18                 | 237.77628                             | 5.2181739      | 6.1676718         | 79.312867                             |
| 20                 | 257.32777                             | 5.3574475      | 6.0581843         | 98.742679                             |
| 22                 | 276.39563                             | 5.4866353      | 5.9608161         | 120.38956                             |
| 24                 | 295.03435                             | 5.6072928      | 5.873293          | 144.27045                             |
| 26                 | 313.28829                             | 5.7206287      | 5.7939149         | 170.40092                             |
| 28                 | 331.19417                             | 5.8276026      | 5.721379          | 198.79537                             |
| 30                 | 348.78283                             | 5.9289902      | 5.6546661         | 229.46725                             |
| 32                 | 366.08054                             | 6.0254282      | 5.5929648         | 262.42911                             |
| 34                 | 383.10987                             | 6.1174461      | 5.5356187         | 297.69279                             |
| 36                 | 399.89045                             | 6.2054895      | 5.4820899         | 335.26944                             |
| 38                 | 416.43944                             | 6.2899374      | 5.4319326         | 375.16963                             |



III-16  
Appendix III-C  
1/2 O<sub>2</sub> Bal He  
90°F-30°F  
Serrated Fin

60 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.635  
1.185748

LBS./CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 77.693773                             | 3.5120189      | 9.3278949         | 1.8891143                             |
| 4                  | 130.66483                             | 4.1765179      | 7.1441977         | 6.8850916                             |
| 6                  | 171.1035                              | 4.6220768      | 6.6683433         | 16.00003                              |
| 8                  | 219.75117                             | 4.9667448      | 6.3500679         | 29.10401                              |
| 10                 | 259.78479                             | 5.2516932      | 6.1136935         | 46.290817                             |
| 12                 | 297.8514                              | 5.4966066      | 5.9271082         | 67.63431                              |
| 14                 | 334.35648                             | 5.7125677      | 5.7738022         | 93.195667                             |
| 16                 | 369.57595                             | 5.9064882      | 5.6442113         | 123.02724                             |
| 18                 | 403.70869                             | 6.0829952      | 5.5323206         | 157.17485                             |
| 20                 | 436.90419                             | 6.2453509      | 5.4341117         | 195.67903                             |

90 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.935  
1.2063636

LBS./CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 37.355578                             | 2.7295924      | 15.374277         | .22251544                             |
| 1                  | 62.824343                             | 3.2460507      | 10.871255         | .74807694                             |
| 1.5                | 85.152303                             | 3.5923456      | 8.8763429         | 1.5241274                             |
| 2                  | 105.65753                             | 3.8602265      | 7.6871384         | 2.5206205                             |
| 2.5                | 124.9059                              | 4.0816926      | 7.245818          | 3.9253998                             |
| 3                  | 143.20853                             | 4.2720429      | 7.0246811         | 5.7352718                             |
| 3.5                | 160.76037                             | 4.439891       | 6.8429861         | 7.9027983                             |
| 4                  | 177.69408                             | 4.5906089      | 6.6893978         | 10.432417                             |
| 4.5                | 194.10528                             | 4.7277927      | 6.5567872         | 13.028813                             |
| 5                  | 210.06585                             | 4.8539774      | 6.4403923         | 16.593046                             |
| 5.5                | 225.63163                             | 4.9710252      | 6.3368812         | 20.230637                             |
| 6                  | 240.84708                             | 5.0803438      | 6.2438363         | 24.243632                             |
| 6.5                | 255.74843                             | 5.1830289      | 6.1594503         | 28.634645                             |
| 7                  | 270.36563                             | 5.2799499      | 6.0823381         | 33.4061                               |
| 7.5                | 284.72389                             | 5.3718096      | 6.0114164         | 38.560252                             |
| 8                  | 299.84462                             | 5.4591847      | 5.9458223         | 44.099214                             |
| 8.5                | 312.74628                             | 5.5425552      | 5.8848523         | 50.024972                             |
| 9                  | 326.44486                             | 5.6223247      | 5.8279524         | 56.339401                             |
| 9.5                | 339.95439                             | 5.6988365      | 5.7746306         | 63.044278                             |
| 10                 | 353.28724                             | 5.7723851      | 5.7244956         | 70.141288                             |
| 10.5               | 366.45439                             | 5.8432251      | 5.6772111         | 77.632041                             |
| 11                 | 379.46565                             | 5.9115786      | 5.6324905         | 85.518071                             |
| 11.5               | 392.32903                             | 5.97764        | 5.5900873         | 93.800847                             |
| 12                 | 405.0549                              | 6.041581       | 5.5497882         | 102.48178                             |
| 12.5               | 417.64806                             | 6.1035541      | 5.5114075         | 111.56282                             |
| 13                 | 430.11587                             | 6.1636949      | 5.4747823         | 121.04347                             |
| 13.5               | 442.46435                             | 6.2221251      | 5.4397693         | 130.9268                              |

III-17  
Appendix III-C  
1/2 O<sub>2</sub> Bal Ho  
90°-300°  
Serrated Pin

130 ATMOSPHERES

|                           |                                       |                |                   |                                       |
|---------------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| DENSITY AT AMB. TEMP. IS: | 1.335                                 | LBS/CU FT      |                   |                                       |
| HEAT CAPACITY IS:         | 1.2194382                             | BTU/LB         |                   |                                       |
| VELOCITY<br>FT/SEC        | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
| .5                        | 49.321839                             | 2.9797247      | 12.866484         | .29033357                             |
| 1                         | 82.949115                             | 3.5435098      | 9.0979778         | .97717176                             |
| 1.5                       | 112.42948                             | 3.9215382      | 7.4388854         | 1.990299                              |
| 2                         | 139.50323                             | 4.2139671      | 7.0838325         | 3.6203292                             |
| 2.5                       | 164.91751                             | 4.4557277      | 6.8201446         | 5.7582213                             |
| 3                         | 189.08309                             | 4.635212       | 6.6119988         | 8.4131605                             |
| 3.5                       | 212.25737                             | 4.8467503      | 6.440978          | 11.592755                             |
| 4                         | 234.61553                             | 5.0112796      | 6.2964127         | 15.303516                             |
| 4.5                       | 256.28379                             | 5.1610345      | 6.1715927         | 19.551143                             |
| 5                         | 277.35708                             | 5.2987831      | 6.0620356         | 24.34071                              |
| 5.5                       | 297.9091                              | 5.4265563      | 5.9646055         | 29.676798                             |
| 6                         | 317.99859                             | 5.5458925      | 5.8770268         | 35.563581                             |
| 6.5                       | 337.67334                             | 5.6579874      | 5.7975982         | 42.004895                             |
| 7                         | 356.97293                             | 5.76379        | 5.7250161         | 49.004295                             |
| 7.5                       | 375.93062                             | 5.8640674      | 5.6582609         | 56.565091                             |
| 8                         | 394.57471                             | 5.9594494      | 5.5965203         | 64.690381                             |
| 8.5                       | 412.92954                             | 6.0504597      | 5.5391377         | 73.383079                             |
| 9                         | 431.01624                             | 6.137539       | 5.485575          | 82.645936                             |
| 9.5                       | 448.85334                             | 6.2210621      | 5.4353857         | 92.481559                             |

170 ATMOSPHERES

|                           |                           |                |                   |                          |
|---------------------------|---------------------------|----------------|-------------------|--------------------------|
| DENSITY AT AMB. TEMP. IS: | 1.735                     | LBS/CU FT      |                   |                          |
| HEAT CAPACITY IS:         | 1.2264841                 | BTU/LB         |                   |                          |
| VELOCITY<br>FT/SEC        | FILM COEF<br>BTU/HR FT2 F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H2O |
| .5                        | 60.381662                 | 3.179202       | 11.286279         | .35322099                |
| 1                         | 101.54945                 | 3.7807296      | 7.9806041         | 1.1888817                |
| 1.5                       | 137.64042                 | 4.1840671      | 7.1147357         | 2.6393179                |
| 2                         | 170.78513                 | 4.4960706      | 6.7751542         | 4.800896                 |
| 2.5                       | 201.89825                 | 4.7546706      | 6.5229565         | 7.6359527                |
| 3                         | 231.48268                 | 4.97572        | 6.3238808         | 11.15667                 |
| 3.5                       | 259.05351                 | 5.1712135      | 6.1603121         | 15.373137                |
| 4                         | 287.22521                 | 5.3467591      | 6.0220463         | 20.29399                 |
| 4.5                       | 313.75232                 | 5.5065394      | 5.9026653         | 25.926786                |
| 5                         | 339.55104                 | 5.6535095      | 5.7978822         | 32.270257                |
| 5.5                       | 364.7116                  | 5.7898364      | 5.7046976         | 39.354476                |
| 6                         | 389.30591                 | 5.9171617      | 5.6209351         | 47.160978                |
| 6.5                       | 413.39248                 | 6.0367607      | 5.5449676         | 55.702853                |
| 7                         | 437.01977                 | 6.1496462      | 5.4755484         | 64.984814                |
| 7.5                       | 460.2285                  | 6.2566367      | 5.411702          | 75.01125                 |

# III-18

Appendix III-D  
Straight Fin  
90° to 30°  
1/2 O<sub>2</sub> bal Hel

## 10 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.135  
.94777778

LBS./CU FT  
BTU/LB

| VELOCITY<br>FT./SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|---------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 4                   | 14.321006                             | 7.4268524      | 4.2655386         | 1.5537231                             |
| 6                   | 19.410735                             | 8.2191633      | 3.147063          | 2.8569326                             |
| 8                   | 24.084966                             | 8.8320658      | 2.5363044         | 4.4018595                             |
| 10                  | 28.472693                             | 9.3387725      | 2.1454523         | 6.1558784                             |
| 12                  | 32.644835                             | 9.7742075      | 1.8712548         | 8.0969762                             |
| 14                  | 36.64583                              | 10.158318      | 1.666951          | 10.208993                             |
| 16                  | 40.505922                             | 10.503155      | 1.5080956         | 12.479406                             |
| 18                  | 44.246907                             | 10.817027      | 1.335586          | 14.416601                             |
| 20                  | 47.88517                              | 11.105735      | 1.3008658         | 17.798273                             |
| 22                  | 51.433437                             | 11.373535      | 1.2702357         | 21.535911                             |
| 24                  | 54.901849                             | 11.623652      | 1.2429029         | 25.629514                             |
| 26                  | 58.298657                             | 11.858592      | 1.2182787         | 30.079002                             |
| 28                  | 61.630695                             | 12.080344      | 1.1959155         | 34.884616                             |
| 30                  | 64.903704                             | 12.290516      | 1.1754649         | 40.046115                             |
| 32                  | 68.12257                              | 12.490427      | 1.1566514         | 45.56358                              |
| 34                  | 71.291496                             | 12.681176      | 1.1392532         | 51.43701                              |
| 36                  | 74.414131                             | 12.863686      | 1.1230895         | 57.666406                             |
| 38                  | 77.493672                             | 13.038742      | 1.1080111         | 64.251767                             |
| 40                  | 80.532936                             | 13.207019      | 1.0938934         | 71.193094                             |

## 30 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.335  
1.128209

LBS./CU FT  
BTU/LB

| VELOCITY<br>FT./SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|---------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                   | 20.040905                             | 7.6433673      | 3.6283828         | .84428773                             |
| 4                   | 33.704651                             | 9.0895467      | 2.1574493         | 2.3925145                             |
| 6                   | 45.683385                             | 10.059237      | 1.5917401         | 4.4016847                             |
| 8                   | 56.68424                              | 10.809354      | 1.300236          | 6.8423145                             |
| 10                  | 67.010806                             | 11.4295        | 1.2325718         | 10.769241                             |
| 12                  | 76.82999                              | 11.962516      | 1.1776519         | 15.507708                             |
| 14                  | 86.246378                             | 12.432522      | 1.1331313         | 21.107713                             |
| 16                  | 95.331149                             | 12.85456       | 1.0959285         | 27.569258                             |
| 18                  | 104.1356                              | 13.2387        | 1.0641286         | 34.892342                             |
| 20                  | 112.69829                             | 13.592043      | 1.0364652         | 43.076966                             |
| 22                  | 121.04918                             | 13.919797      | 1.0120607         | 52.123120                             |
| 24                  | 129.21213                             | 14.225909      | .99028323         | 62.03083                              |
| 26                  | 137.20655                             | 14.513447      | .97066395         | 72.800072                             |
| 28                  | 145.04854                             | 14.784844      | .95284603         | 84.430853                             |
| 30                  | 152.7516                              | 15.042068      | .93655206         | 96.923173                             |
| 32                  | 160.32724                             | 15.286735      | .92156239         | 110.27703                             |
| 34                  | 167.78535                             | 15.520187      | .90770036         | 124.49243                             |
| 36                  | 175.1345                              | 15.743557      | .89482191         | 139.56407                             |
| 38                  | 182.38224                             | 15.957804      | .88280816         | 155.50785                             |

## 60 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.635  
1.185748

LBS/CU FT  
BTU/LB

III-19  
Appendix III-D  
Straight Fin  
90° to 30° F  
1/2 O<sub>2</sub> bal Hel

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| 2                  | 34.02647                              | 8.9101221      | 2.2463344         | 1.15637                               |
| 4                  | 57.225473                             | 10.595981      | 1.3208851         | 3.2450852                             |
| 6                  | 77.563578                             | 11.72638       | 1.1905543         | 7.3014416                             |
| 8                  | 96.24139                              | 12.600815      | 1.1107275         | 12.980341                             |
| 10                 | 113.77436                             | 13.32374       | 1.0504612         | 20.281782                             |
| 12                 | 130.44587                             | 13.945095      | 1.0036556         | 29.205767                             |
| 14                 | 146.43349                             | 14.492996      | .96571282         | 39.752293                             |
| 16                 | 161.85808                             | 14.984979      | .93400674         | 51.921363                             |
| 18                 | 176.80672                             | 15.432784      | .90690517         | 65.712975                             |
| 20                 | 191.9449                              | 15.844687      | .88332904         | 81.127129                             |

## 90 ATMOSPHERES

DENSITY AT AMB. TEMP. IS:  
HEAT CAPACITY IS:

.935  
1.2063636

LBS/CU FT  
BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 16.360107                             | 6.9250769      | 4.7526189         | .17465679                             |
| 1                  | 27.514311                             | 8.2353508      | 2.8259241         | .4947904                              |
| 1.5                | 37.292979                             | 9.1169138      | 2.0049327         | .91009658                             |
| 2                  | 46.273371                             | 9.7935377      | 1.6803045         | 1.4026242                             |
| 2.5                | 54.703315                             | 10.355405      | 1.3486074         | 1.8624262                             |
| 3                  | 62.719065                             | 10.838331      | 1.2885172         | 2.6818938                             |
| 3.5                | 70.406                                | 11.264168      | 1.2398054         | 3.6503554                             |
| 4                  | 77.822223                             | 11.646545      | 1.1991004         | 4.7678111                             |
| 4.5                | 85.00961                              | 11.994585      | 1.1643067         | 6.034261                              |
| 5                  | 91.999643                             | 12.314722      | 1.1340391         | 7.4497049                             |
| 5.5                | 98.81677                              | 12.611675      | 1.1073371         | 9.0141429                             |
| 6                  | 105.48047                             | 12.88902       | 1.0835095         | 10.727575                             |
| 6.5                | 112.06661                             | 13.149536      | 1.0620432         | 12.590001                             |
| 7                  | 118.40831                             | 13.395429      | 1.0425479         | 14.601422                             |
| 7.5                | 124.69659                             | 13.62848       | 1.02472           | 16.761836                             |
| 8                  | 130.88086                             | 13.850154      | 1.0083192         | 19.071244                             |
| 8.5                | 136.96917                             | 14.061668      | .99315219         | 21.529647                             |
| 9                  | 142.96855                             | 14.264046      | .97906135         | 24.137044                             |
| 9.5                | 148.88514                             | 14.458159      | .96591661         | 26.893435                             |
| 10                 | 154.72434                             | 14.644755      | .95360943         | 29.79882                              |
| 10.5               | 160.49097                             | 14.824479      | .94204039         | 32.853199                             |
| 11                 | 166.18934                             | 14.997894      | .93115582         | 36.056572                             |
| 11.5               | 171.82329                             | 15.165494      | .92086523         | 39.408939                             |
| 12                 | 177.39631                             | 15.327715      | .91111925         | 42.9103                               |
| 12.5               | 182.91156                             | 15.484943      | .90186811         | 46.560656                             |
| 13                 | 188.37191                             | 15.637522      | .89306835         | 50.360005                             |
| 13.5               | 193.78001                             | 15.785762      | .8846818          | 54.308349                             |

III-20  
Appendix III-D  
Straight Fin  
90°F to 30°F  
1/2 O<sub>2</sub> bal Hel

130 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.335 LBS/CU FT  
HEAT CAPACITY IS: 1.2194382 BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 21.600805                             | 7.5596719      | 3.6385701         | .2085735                              |
| 1                  | 36.328079                             | 8.9900156      | 2.1635067         | .59105778                             |
| 1.5                | 49.239188                             | 9.9490877      | 1.5962092         | 1.0874253                             |
| 2                  | 61.096303                             | 10.690991      | 1.3045046         | 1.6395931                             |
| 2.5                | 72.226645                             | 11.304346      | 1.2337243         | 2.6556141                             |
| 3                  | 82.810113                             | 11.831526      | 1.178753          | 3.3240344                             |
| 3.5                | 92.959434                             | 12.296385      | 1.1341908         | 5.2050037                             |
| 4                  | 102.75133                             | 12.713802      | 1.0969533         | 6.7983722                             |
| 4.5                | 112.24108                             | 13.093736      | 1.0651236         | 8.6041898                             |
| 5                  | 121.47025                             | 13.443209      | 1.0374343         | 10.622457                             |
| 5.5                | 130.47114                             | 13.767374      | 1.013007          | 12.853172                             |
| 6                  | 139.26945                             | 14.070135      | .99120916         | 15.296337                             |
| 6.5                | 147.88613                             | 14.354524      | .97157153         | 17.951952                             |
| 7                  | 156.33851                             | 14.622949      | .95373696         | 20.820015                             |
| 7.5                | 164.64115                             | 14.877356      | .93742775         | 23.900527                             |
| 8                  | 172.80644                             | 15.119344      | .92242406         | 27.193489                             |
| 8.5                | 180.84505                             | 15.35024       | .90854907         | 30.6989                               |
| 9                  | 188.76624                             | 15.571164      | .89565859         | 34.416759                             |
| 9.5                | 196.5781                              | 15.783065      | .8836336          | 38.347068                             |

170 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.735 LBS/CU FT  
HEAT CAPACITY IS: 1.2264841 BTU/LB

| VELOCITY<br>FT/SEC | FILM COEF<br>BTU/HR FT <sup>2</sup> F | LENGTH<br>FEET | FRICT. FACT.<br>F | PRES. DROP<br>INCHES H <sub>2</sub> O |
|--------------------|---------------------------------------|----------------|-------------------|---------------------------------------|
| .5                 | 26.444523                             | 8.0637532      | 2.9892834         | .23775881                             |
| 1                  | 44.47421                              | 9.5918511      | 1.7774385         | .67394273                             |
| 1.5                | 60.280478                             | 10.615128      | 1.3128822         | 1.2415835                             |
| 2                  | 74.796407                             | 11.406698      | 1.2217773         | 2.2072596                             |
| 2.5                | 88.422593                             | 12.061114      | 1.155483          | 3.4489431                             |
| 3                  | 101.37928                             | 12.623586      | 1.1039979         | 4.9663341                             |
| 3.5                | 113.80446                             | 13.119565      | 1.0622613         | 6.7597325                             |
| 4                  | 125.79296                             | 13.564926      | 1.0273858         | 8.8290384                             |
| 4.5                | 137.40977                             | 13.970294      | .99757473         | 11.174852                             |
| 5                  | 148.70848                             | 14.343163      | .97164152         | 13.795372                             |
| 5.5                | 159.72771                             | 14.689029      | .94876334         | 16.692401                             |
| 6                  | 170.49894                             | 15.012058      | .92834789         | 19.865336                             |
| 6.5                | 181.0478                              | 15.315486      | .90995566         | 23.314179                             |
| 7                  | 191.39552                             | 15.60188       | .89325212         | 27.03893                              |
| 7.5                | 201.55993                             | 15.873319      | .87797723         | 31.039588                             |

## IV. Adsorption

### A. General:

The use of an adsorbent to remove CO<sub>2</sub> and/or water is attractive in that it permits a self-contained system that can be regenerated from outside of the vessel if required.

Adsorbents have been used to remove CO<sub>2</sub> from the atmosphere in several applications. Great Britain and France both have programs to develop molecular sieve systems for submarines. In addition several systems have been designed for space use. At least one of these uses an adiabatic desorption cycle (see Ref. 1 and 2). In a space application, the convenience of a readily available high vacuum simplifies the equipment needed for reactivation.

### B. Moisture Removal:

Many adsorbents are used to dry gases. Among the more popular are silica gel, activated alumina and molecular sieve. Each of these has properties which make it desirable for certain purposes. Silica gel can be reactivated at a relatively low temperature. Activated alumina has somewhat greater capacity but requires a higher reactivation temperature. Type 13X Molecular Sieve will produce an extremely dry gas. This material (Type 13X MS) will adsorb about 25% water by weight and maintain a very low partial pressure of water (See Fig. IV-1 and Ref. 3). The dimensionless plot shown in Fig. IV-2 indicates the relatively high adsorption potential for water at 77°F. The 400°F curve is included for the reactivation cycle.

Figure IV-3 is a plot of the isotherm curves for silica gel as taken from Ref. 4. These are plotted in dimensionless form in Fig. IV-4. Comparing the shape of the curves in Fig. IV-3 and Fig. IV-1 it is obvious that molecular sieve will have a higher capacity for water, at low partial pressures, than will silica gel. Conversely, it is much easier to remove the water from silica gel.

### C. CO<sub>2</sub> Removal:

Either Type 5A Molecular Sieve or Type 4A could be used for the removal of CO<sub>2</sub>. Type 5A has a slightly greater capacity. The isotherms of 5A Sieve are shown in Fig. IV-5. A dimensionless plot of the CO<sub>2</sub> isotherms for 5A Molecular Sieve is shown in Figure IV-6. There is a significant increase in the amount of CO<sub>2</sub> that can be adsorbed at 32°F over that at 77°F as shown in IV-5. In addition the adsorption efficiency is enhanced (smaller R in IV-6) resulting in a sharper "break-through" curve.

Comparison of Figs. IV-2 and IV-6 shows that molecular sieves have a much stronger adsorption potential for water than for CO<sub>2</sub>. (5A

Molecular Sieve water isotherms are similar to 13X.) For this reason it is necessary to remove essentially all of the water prior to adsorbing  $\text{CO}_2$ . Otherwise the water will displace the  $\text{CO}_2$ .

Referring to Fig. IV-4, water vapor can be removed by reducing the gas temperature or by an adsorbent or by a combination of low temperature and adsorption.

#### D. Reactivation:

There are two possible cycles to consider in designing an adsorption bed of this type. An adiabatic desorption by lowering the pressure is practical if a source of low pressure is readily available. In this case the quantity of adsorbed material would follow the isotherm to the new equilibrium pressure. It is necessary to have a relatively high vacuum to remove much water if the adsorbent is at ambient temperature. In the case of  $\text{CO}_2$ , an adiabatic desorption is possible by either lowering the adsorbent pressure or by purging with a gas having a low partial pressure of  $\text{CO}_2$ .

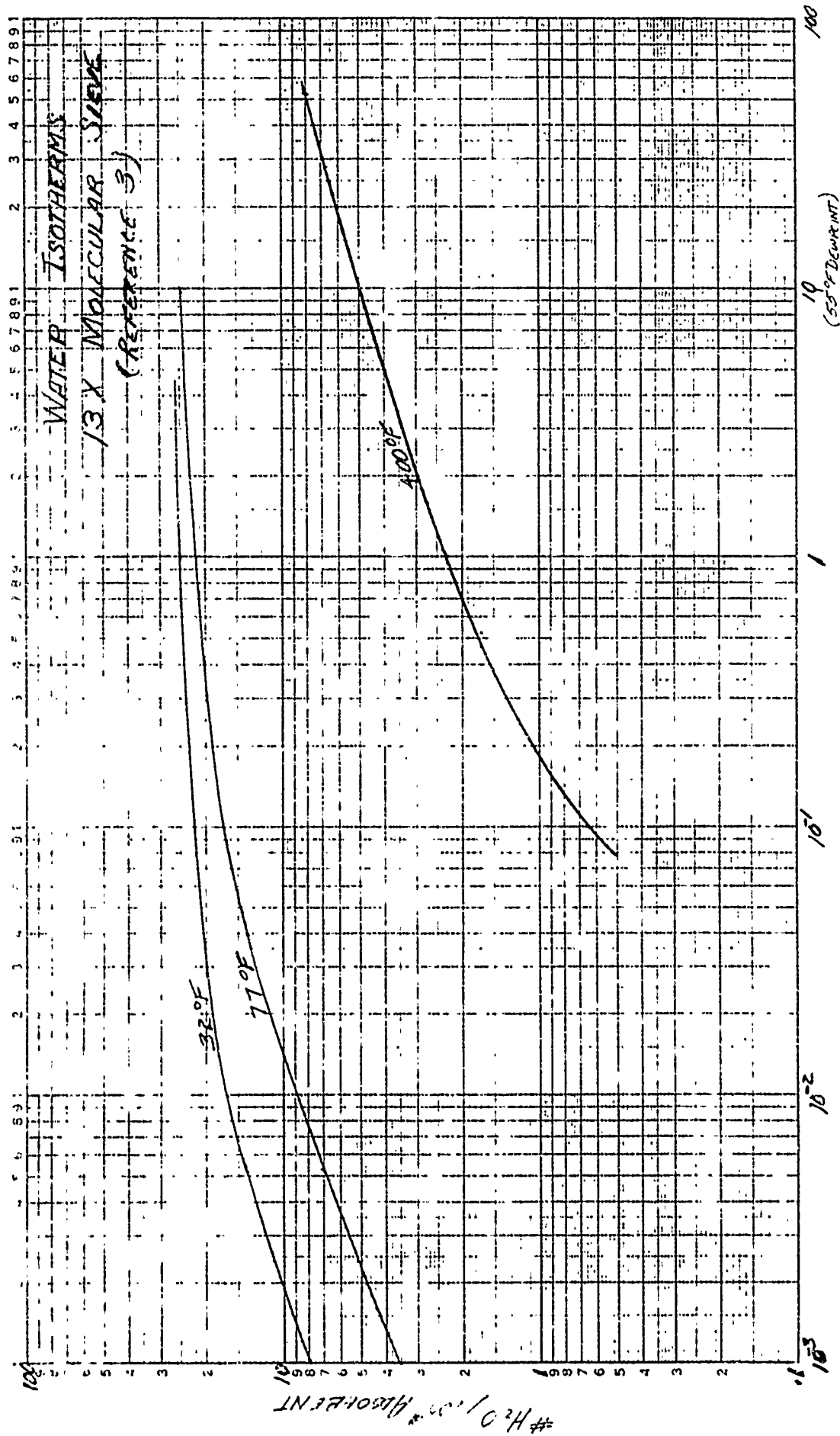
The other cycle for desorption is to raise the temperature. This is the more common approach. In the case of water adsorbed on molecular sieve it is necessary to increase the temperature to over  $400^\circ\text{F}$  before reactivation is very effective. Carbon dioxide can be removed at  $212^\circ\text{F}$  with reasonable efficiency.

#### E. Dimensionless Isotherm Plots:

The dimensionless plots of adsorption isotherms (Fig. IV-2, 4, 6) are useful in determining the adsorption efficiency. The curves in Fig. IV-2 were obtained from the data in IV-1 by dividing the partial pressure of water at a given adsorbent loading by the partial pressure when no more moisture will be adsorbed or  $\frac{C}{C_0}$ . The ordinate for the curve is the concentration ratio  $\frac{q}{Q}$  or weight percent (at the corresponding water partial pressure) divided by the maximum weight percent, when no more water will be adsorbed.

The shape of the isotherm curve as plotted above will give an indication of the ease with which the adsorbent can remove water (or  $\text{CO}_2$ ). The shape of the curve determines the "R" factor (see Ref. 5 for a more detailed review of the mechanism of adsorption). For ideal adsorption, the isotherm would be a horizontal line on Fig. IV-1 and IV-2. In other words, the adsorbent would have maximum capacity regardless of the concentration of water vapor in the gas. This would give an "R factor" of zero.

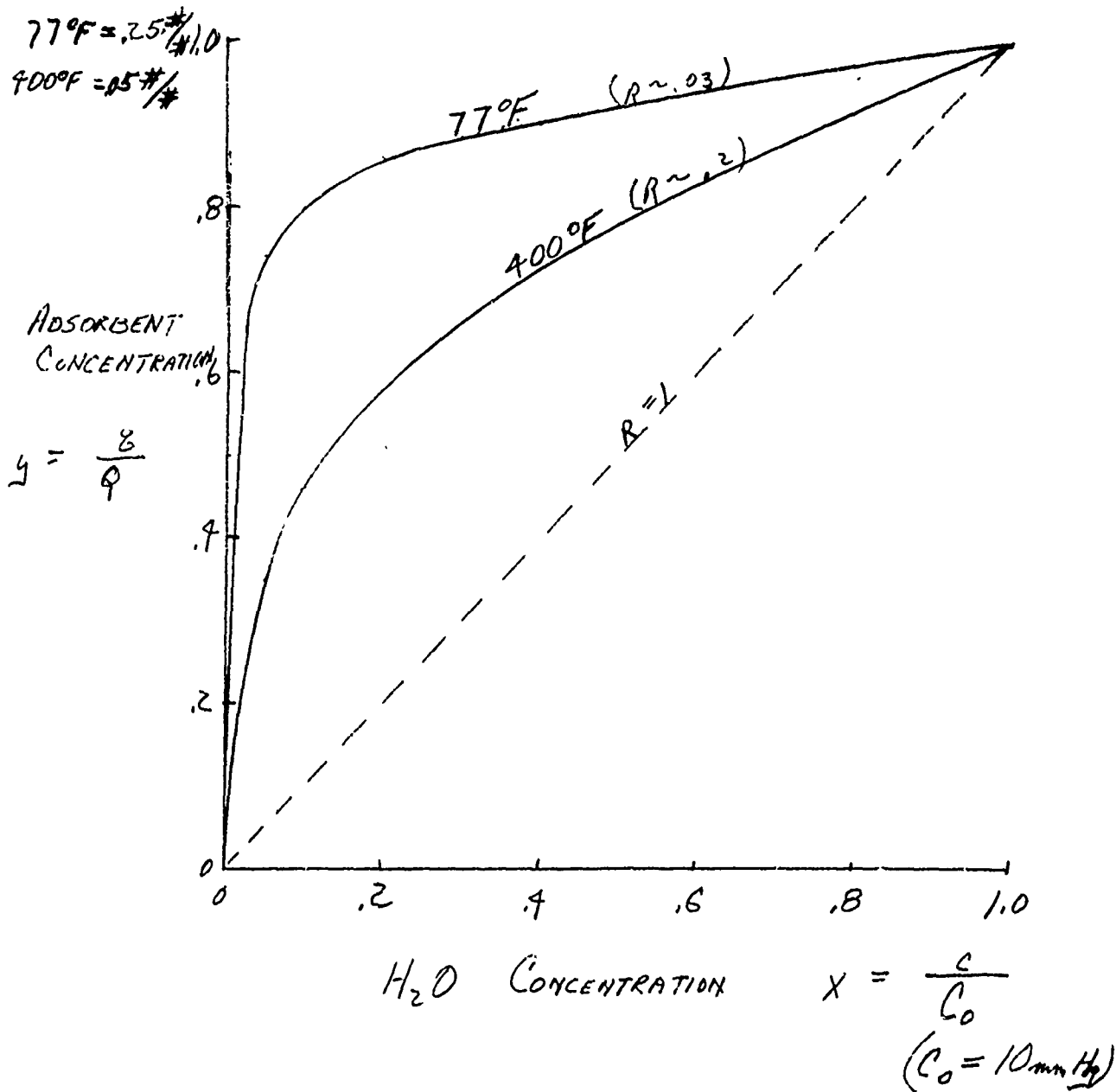
A curve with an "R factor" greater than 1 will result in unfavorable adsorption. It is desirable to have a small R during the adsorption part of the cycle and large R during the desorption phase.



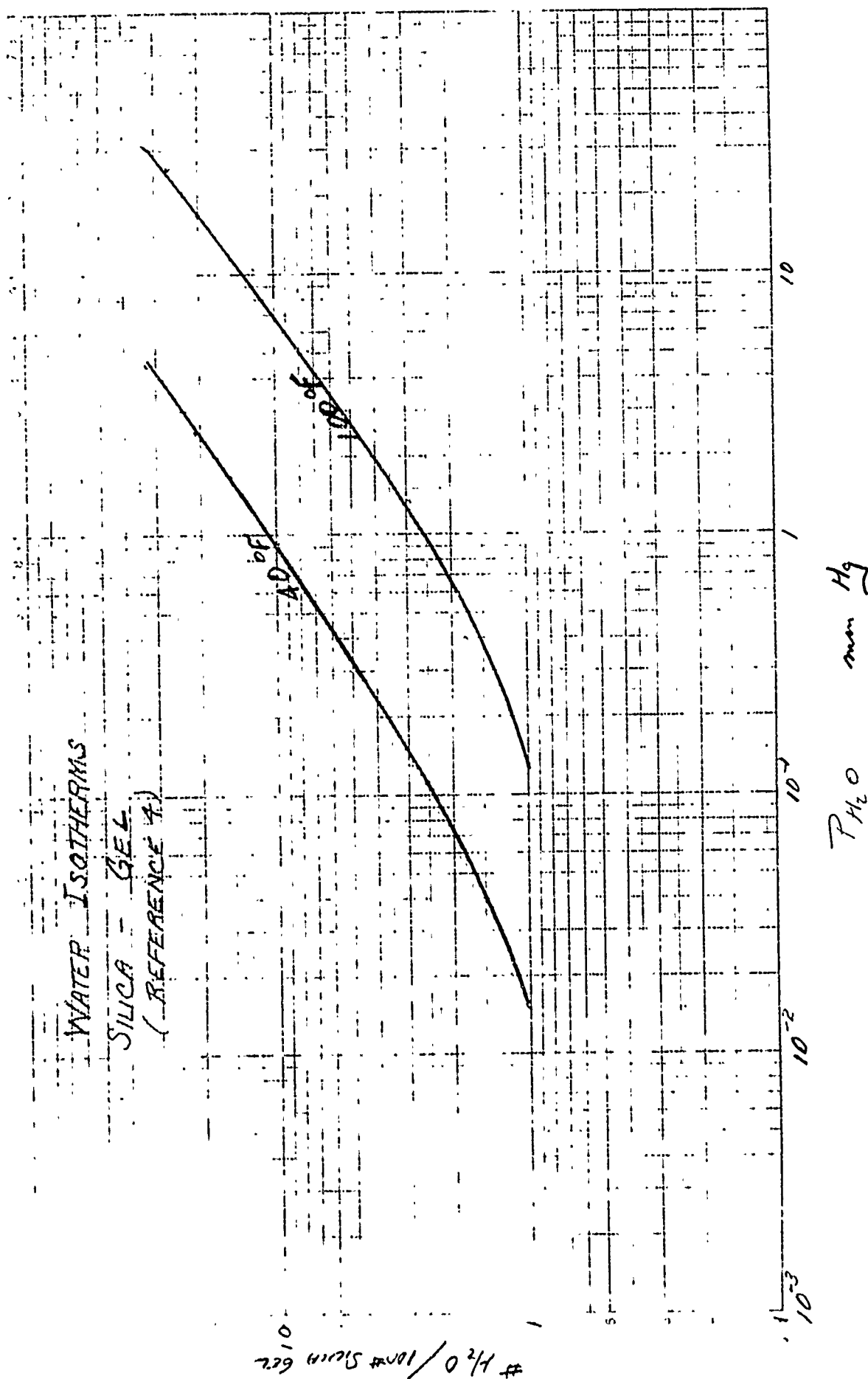


TITLE: H<sub>2</sub>O ADSORPTION ISOTHERMS  
13X MOLECULAR SIEVE  
 BY: \_\_\_\_\_ DATE: \_\_\_\_\_

IV-4  
 JOHN M. CANTY, P. E.  
 ENGINEERING CONSULTANT  
 117 CORNWALL AVENUE,  
 TONAWANDA, NEW YORK 14150  
 (716) 832-6554

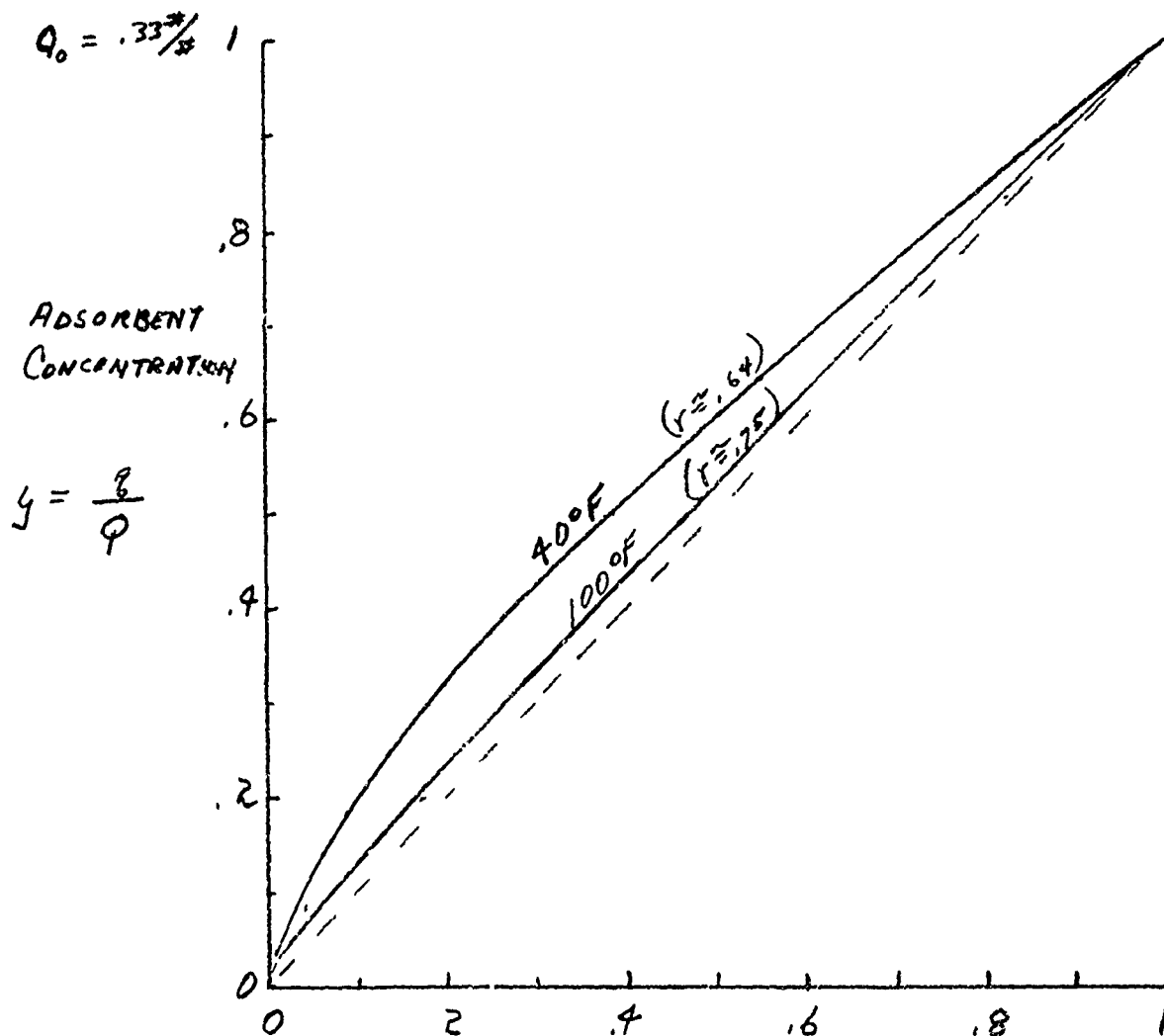


DIMENSIONLESS ISOTHERMS  
 13X MOLECULAR SIEVE  
 (DATA FROM UCC F-3036-3)



TITLE: H<sub>2</sub>O ADSORPTION ISOTHERMS  
SILICA GEL  
 BY: \_\_\_\_\_ DATE: \_\_\_\_\_

IV-6  
 JOHN M. CANTY, P. E.  
 ENGINEERING CONSULTANT  
 117 CORNWALL AVENUE  
 TONAWANDA, NEW YORK 14150  
 (716) 832-6554



H<sub>2</sub>O CONCENTRATION  $x = \frac{C}{C_0}$

40°F  $C_0 = 4.5 \text{ mm Hg}$   
 100°F  $C_0 = 33 \text{ mm Hg}$

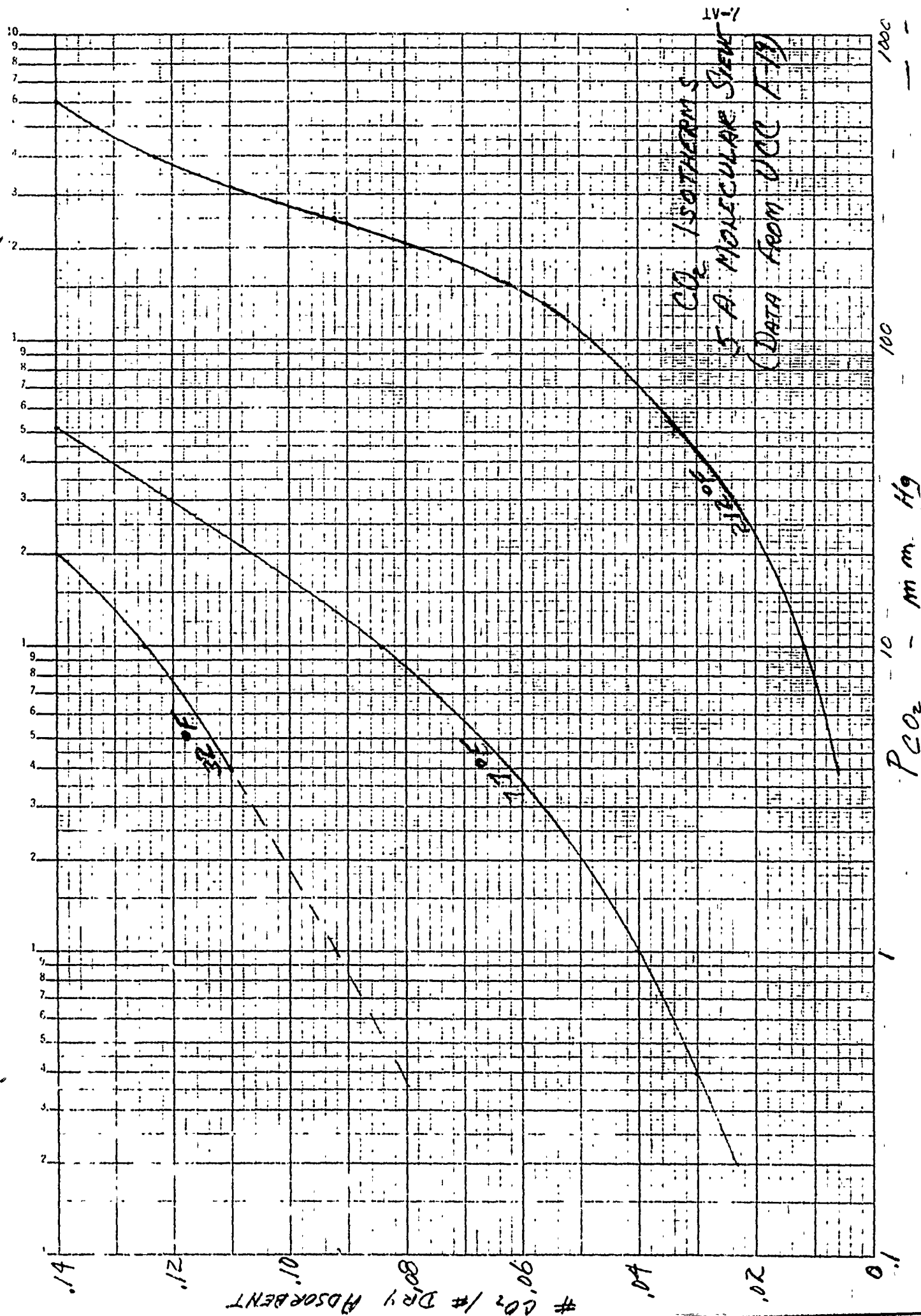
DIMENSIONLESS ISOTHERMS

SILICA GEL

(DATA FROM TECH BUL 202 - DAVISON DIV - W. R. GRACE)

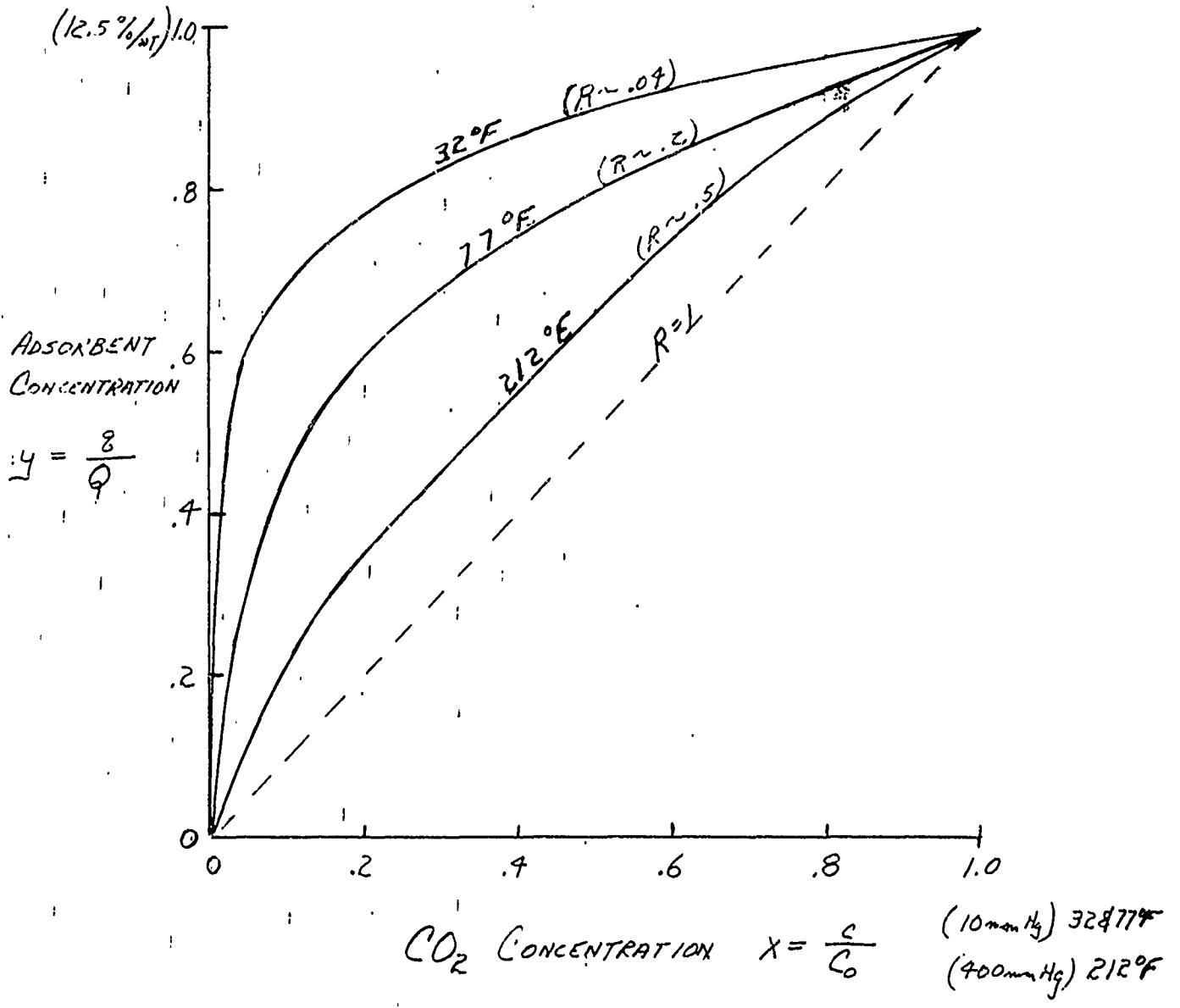
K.E. SEMI LOGARITHMIC 46 5010

3 CYCLES 2 IN DIVISION  
OF P.P.S. SYSTEM



TITLE: CO<sub>2</sub> ADSORPTION ISOTHERMS  
5A MOLECULAR SIEVE  
 BY: \_\_\_\_\_ DATE: \_\_\_\_\_

IV-8  
 JOHN M. CANTY, P. E.  
 ENGINEERING CONSULTANT  
 117 CORNWALL AVENUE  
 TONAWANDA, NEW YORK 14150  
 (716) 832-6554



5-A MOLECULAR SIEVE  
 (DATA FROM UNION CARBIDE CORP.  
 F-19 "LINDE MOLECULAR SIEVES")

### F. Adsorption "Efficiency":

The effectiveness of an adsorbent depends on the ease with which the material being adsorbed can reach the adsorbent ( a function of the diffusivity and void space of the bed), the contact time (a function of velocity and bed length) and the equilibrium curve characteristic.

The dimensionless parameter which relates these variables is called the Peclet Number:

$$P_e = \frac{d_p V_s}{D_v F}$$

where:  $d_p$  = Equivalent diameter of the adsorbent particle, ft.

$V_s$  = Superficial velocity of bed (with no adsorbent), ft/sec

$D_v$  = Diffusivity of the gases ft<sup>2</sup>/sec

$F$  = Fractional void space of adsorbent bed

When the Peclet number is greater than 20, the diffusion of the gas is controlling and the number of reaction units can be determined by:

$$N = \frac{2.5 b}{d_p P_o}$$

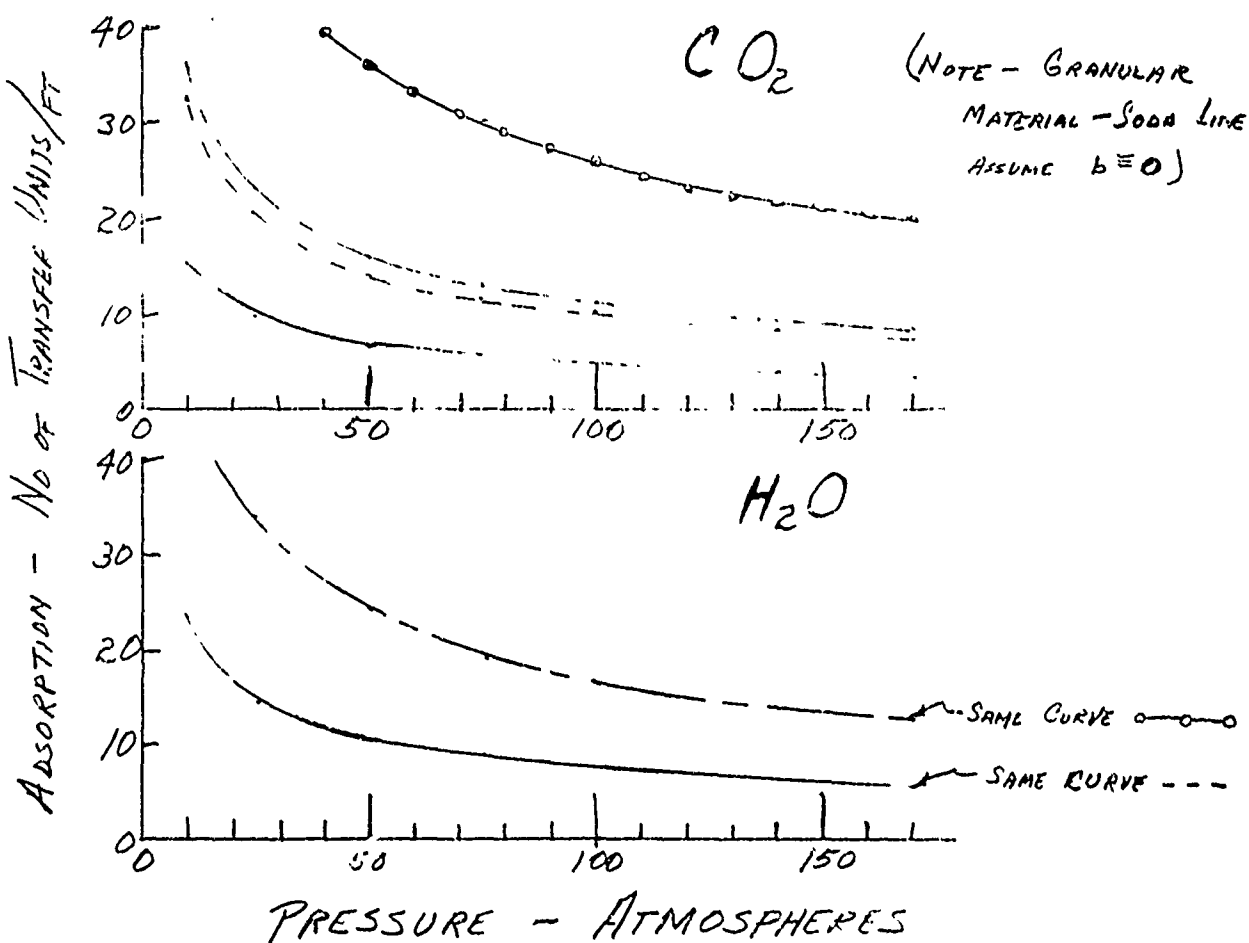
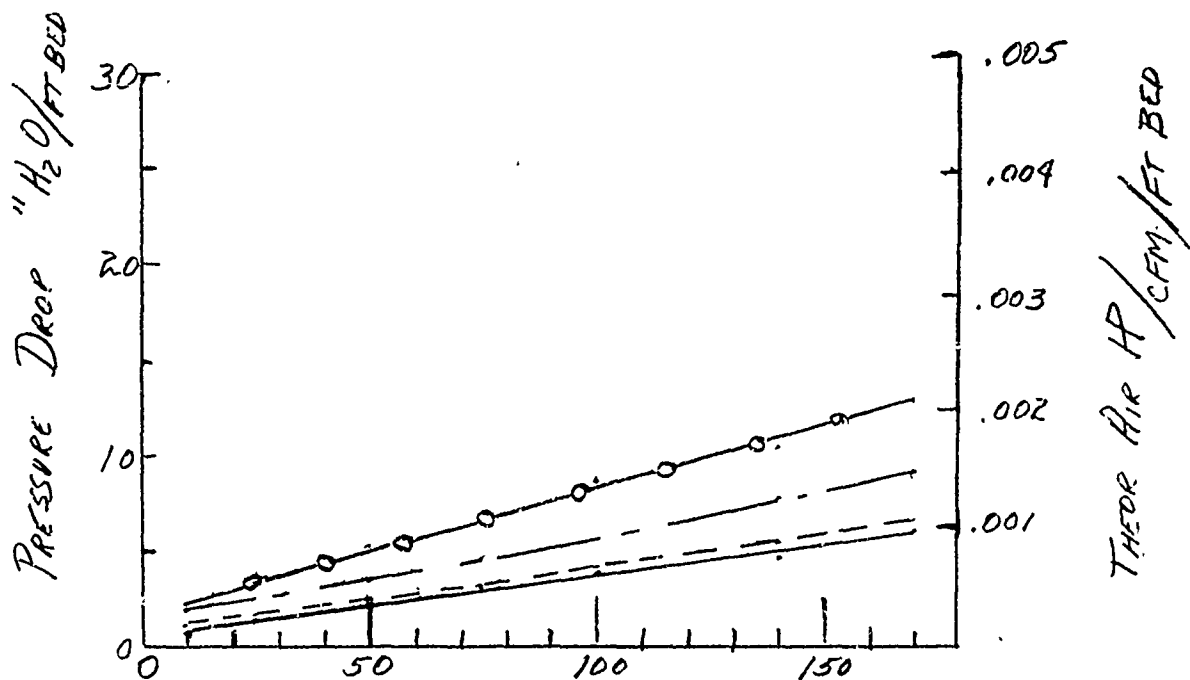
Where:  $N$  = Number of reaction units per ft. of bed

(It is desirable to have a large number of reaction units since this will result in a much sharper "break through" curve, see Ref. 5)

$$b = \text{Isotherm adsorption factor} = \frac{2}{1 + R}$$

At a given temperature, the diffusivity varies inversely as the pressure. In the case of an adsorbent system for diving it is necessary to increase the contact time (either by reducing the velocity or increasing the bed length) to compensate for this. Another method of improving the adsorption efficiency is to decrease the particle size of the adsorbent at the penalty of a higher pressure drop.

Figures IV-7, IV-8 and IV-9 show the number of reaction units per foot of adsorbent bed for superficial velocities of .5, 1 and 3 ft. per second and as a function of pressure (depth). Each graph shows values for water and for CO<sub>2</sub> for four adsorbents, 1/8 and 1/16 molecular sieve and 4-8 and 8-12 mesh granular material. The latter materials would be silica gel or activated alumina for water and soda lime or baralytyme for removing CO<sub>2</sub> (in this case it is a chemical reaction rather than adsorption but diffusion would be controlling). Values of pressure drop for each adsorbent as a function of pressure are also shown.

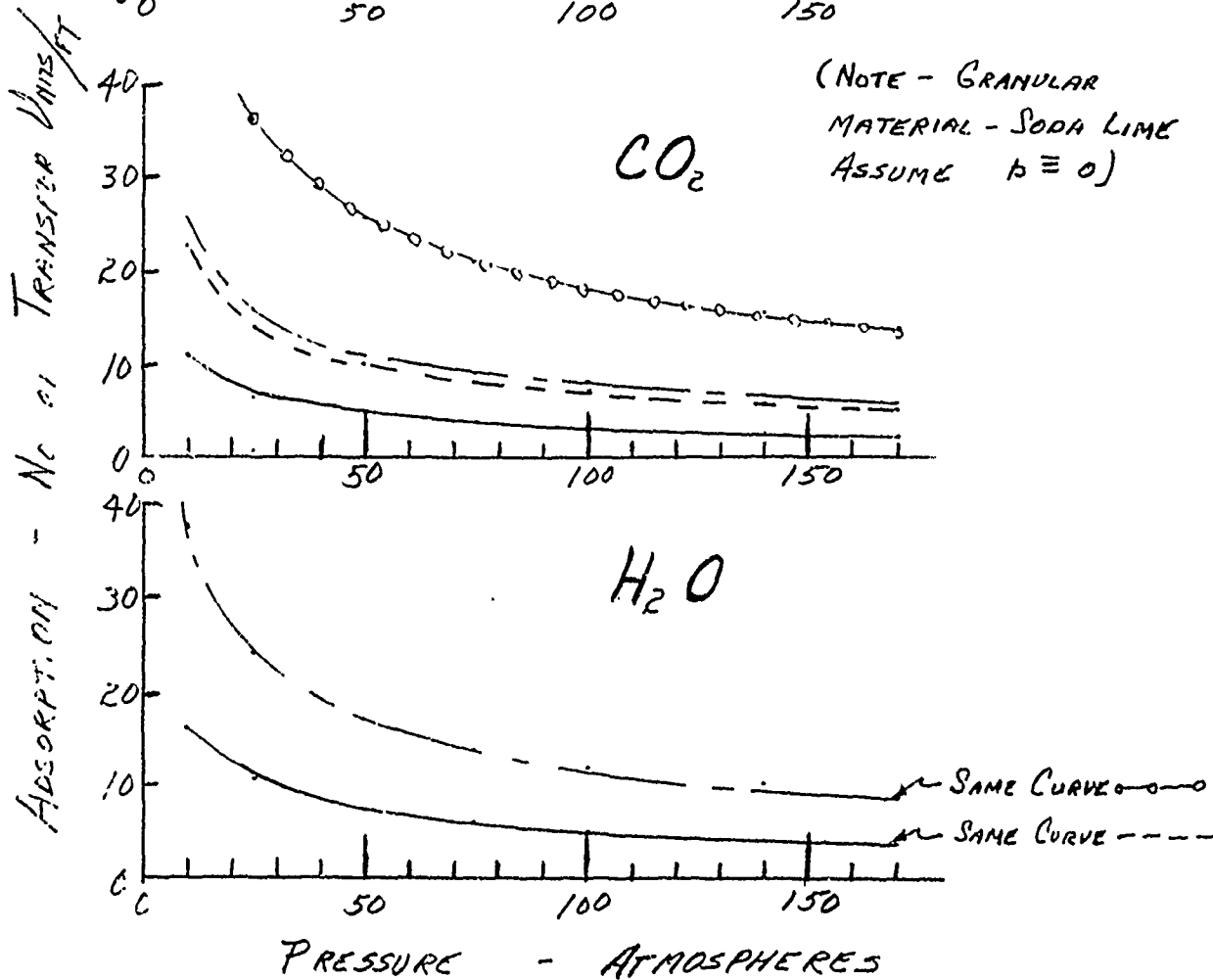
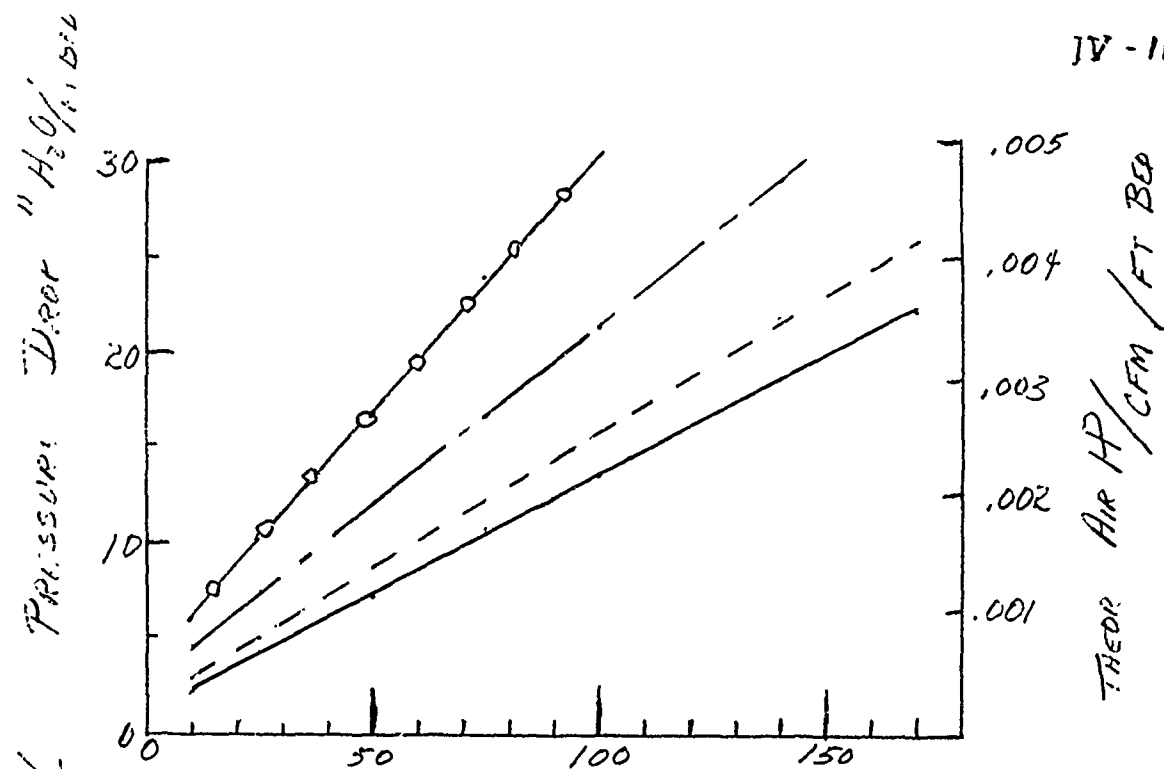


LEGEND

- 1/8 MOL SIEVE
- - - 1/16 " "
- - - - 4-8 MESH GRAN
- o-o-o-o 8-14 " "

ΔP & ADSORPTION EFFICIENCY  
SUPERFICIAL VELOCITY 0.5'/SEC

FIG IV-7



LEGEND

— 1/4" Sieve

- - - 1/8 " "

- - - 4-8 Mesh Granular

- o - 8-19 " "

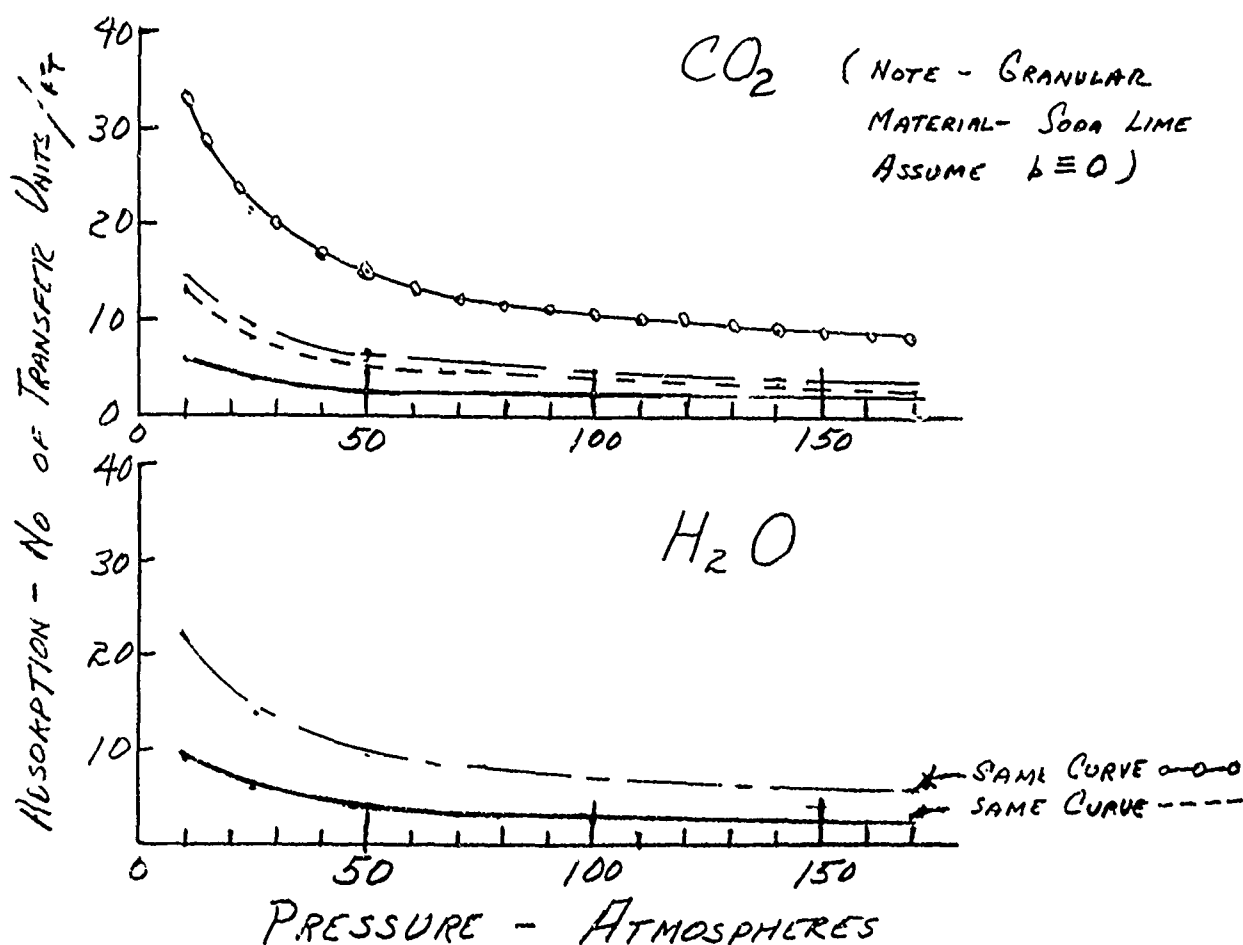
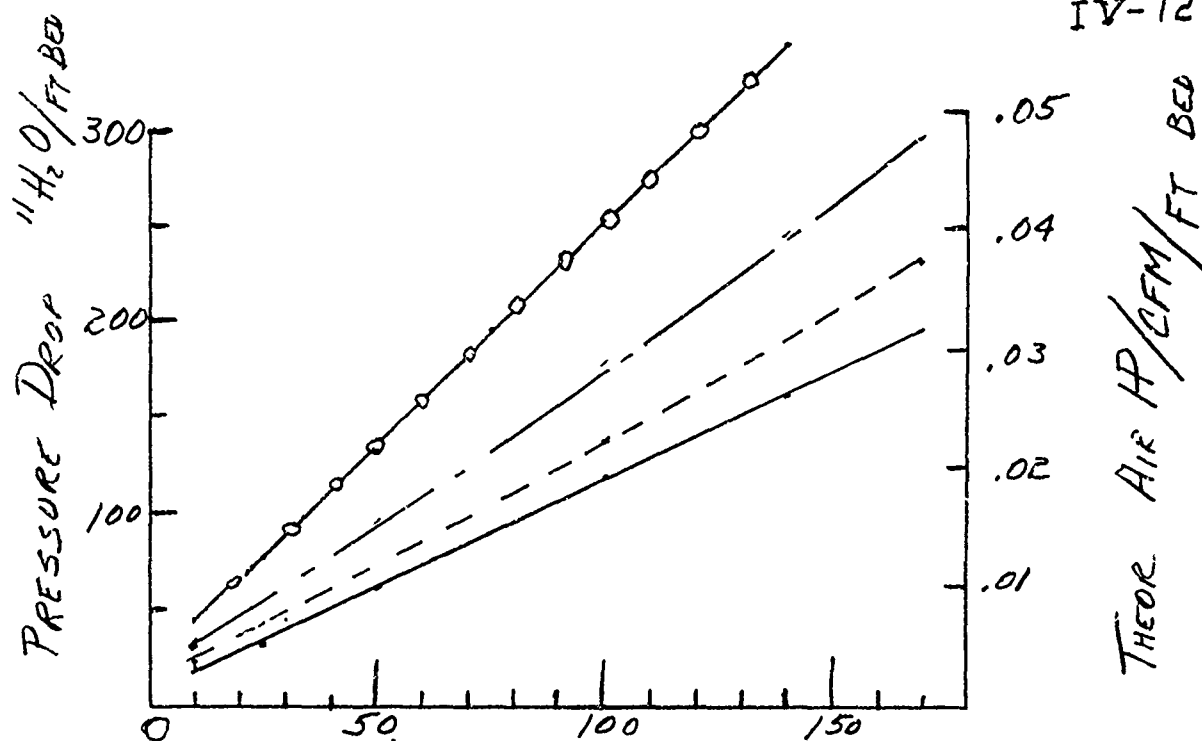
$\Delta P$  & Adsorption Efficiency

Superficial Vel 1 FT/SEC.

FIG IV-8



IV-12



LEGEND

—  $\frac{1}{8}$  Mol Sieve  
 ---  $\frac{1}{16}$  " "  
 - - - 4-8 Mesh Gran  
 $\circ-\circ-\circ-\circ$  8-14 " "

$\Delta P$  & Adsorption Efficiency

Superficial Velocity  $3'/\text{SEC}$

FIG IV-9

References:

1. "Skylab Environmental Control and Life Support Systems" G. D. Hopson, J. W. Littles and W. C. Patterson. ASME Paper 71 AV-14 also Mechanical Engineering Vol. 94, No. 5, May 1972, p 35-40.
2. "A Regenerative Carbon Dioxide Removal System for the AAP Cluster" J. P. Gillerman, SAE paper 690626, National Aeronautics and Space Engineering and Manufacturing Meeting, Los Angeles, Calif. October 6-10, 1969.
3. Linde Molecular Sieves - Water and Air Data Sheets #F3035 - Union Carbide Corp.
4. Technical Bulletin 202, Davison Chemical Div., W. R. Grace & Co.
5. "Chemical Engineers Handbook", R. H. Perry, C. H. Chilton, S. D. Kirkpatrick, 4th Edition, Section 16.

## V. Comparison of Low Temperature, Adsorption and Chemical Removal Systems

### A. General:

The results given in this section of the report pertain to evaluation of a three man module using 18 cfm gas flow. Information given in the physiological portion of this report (Section I) indicates that this provides an expected level of CO<sub>2</sub> pressure ranging between 1.2 millimeters of mercury and 4 millimeters of mercury. The following design parameters were used in the evaluation of the environmental control system:

Pressure - 10 atmospheres to 170 atmospheres

Chamber volume - Sphere 180 cu. ft.  
Cylindrical section 540 cu. ft.

Dry bulb temperature - 85°F

Relative humidity - 50%

Gas - Helium + 1/2 ATA O<sub>2</sub>

Although the results given in this section are specific to the High Pressure Research Facility at the State University of New York at Buffalo, data given in the balance of the report are presented in a general way so that they can be extrapolated for the design of other systems with different flow rates and chamber sizes.

### B. Cooling to Remove CO<sub>2</sub>:

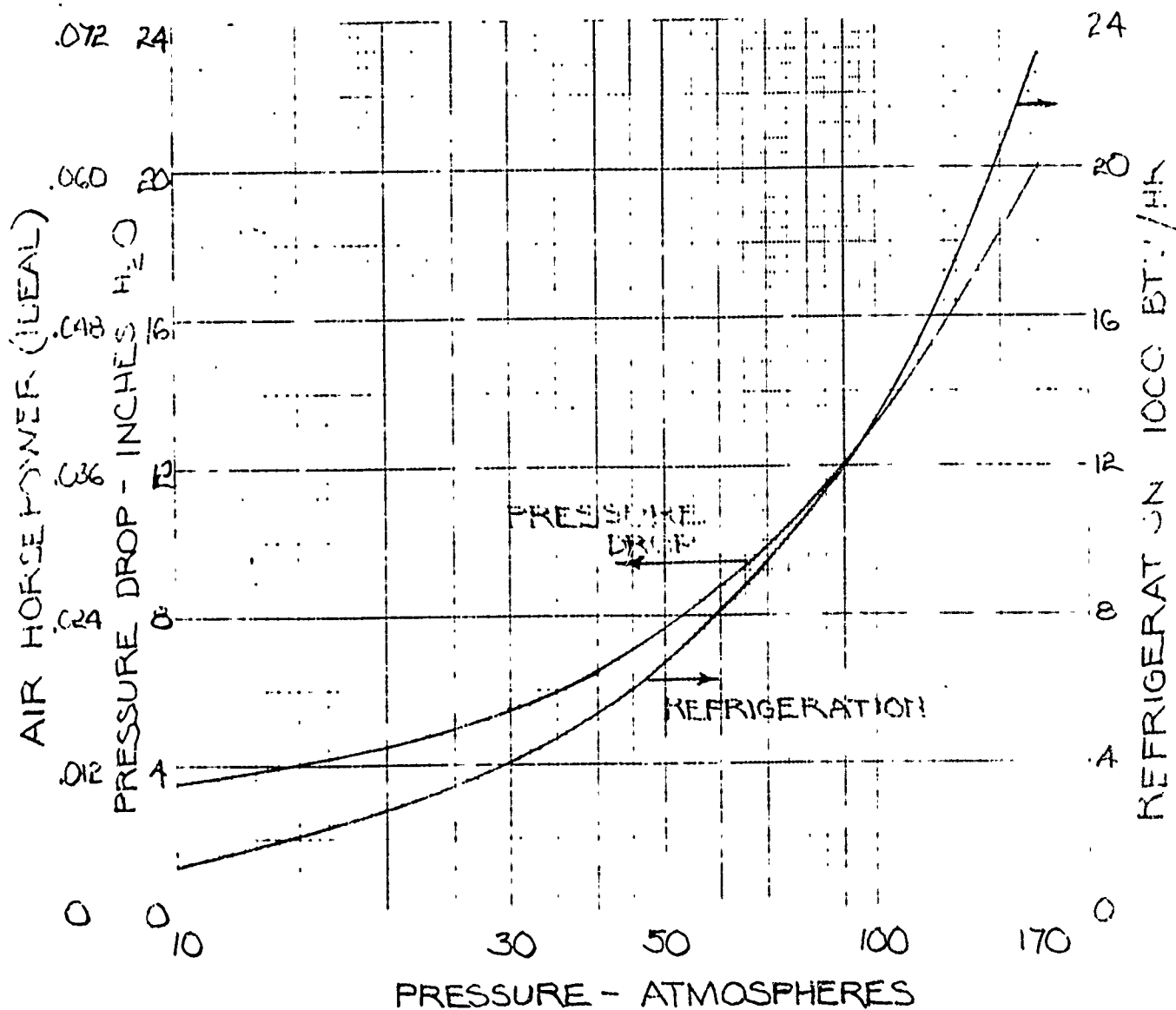
The use of a compact counterflow heat exchanger to cool the gas and remove water and CO<sub>2</sub> has the advantage that no high pressure equipment is required if the heat exchanger is kept within the confines of the chamber environment.

Functionally this is the simplest of all systems. However, it requires a source of very low temperature refrigeration since the carbon dioxide will not start to condense until the temperature reaches -190°F. A 10° temperature drop across the refrigeration portion of the equipment is necessary to condense most of the CO<sub>2</sub> and to provide an adequate "driving force" for the heat exchanger.

The results for a three man module are shown in Fig. V-1. Design data for compact heat exchangers is given in Section III.

Where the refrigeration is available this could be a very promising system for pressures up to 30 atmospheres (about 1,000 ft. of depth). However, the refrigeration requirement becomes prohibitive at very high pressures. It is necessary to add an amount of heat to the chamber

SERRATED FIN  
 $7\frac{3}{4}'$  LONG,  $5'' \times 5''$  CROSS SECTION  
 VEL. -  $4'/\text{SEC}$  FLOW - 18 CFM  
 $\Delta T - 10^\circ \text{F.}$



HEAT EXCHANGER - CO<sub>2</sub> REMOVAL  
3 MAN MODULE

FIG. V-1

equivalent to the refrigeration supplied in order to avoid lowering the overall chamber temperature (the heat of condensation of  $H_2O$  and  $CO_2$  contributed very little in this case). This heat is in addition to that required due to heat loss of the walls of the chamber or habitat.

A system similar to this has been proposed for space applications, and some test results are available indicating that it is technically feasible (see Ref. 1). The results shows that  $CO_2$  can be condensed and revaporized at 1 atmosphere. Since the diffusivity of the gas is inversely proportional to pressure, additional test work needs to be done at high pressures to verify the efficacy of removing  $CO_2$  under these conditions.

#### C. Cooling for Humidity Control:

Cooling the gas to remove water appears to be a practical method. Standard refrigeration equipment (e.g. Freon) can be used to remove heat to maintain the temperature difference. Countercurrent heat exchangers are also indicated for this cooling to reduce the total refrigeration requirements and size of the cooling coils.

The resulting pressure drop and refrigeration requirements for a three man 18 cfm module cooling the gas to  $32^{\circ}F$  is shown in Fig. V-2. This is based on a driving force across the heat exchanger of  $3^{\circ}F$ . It is possible to reduce the length of the heat exchanger by increasing the temperature difference at some penalty in refrigeration power cost and increased replacement of heat.

#### D. Humidity Control by Adsorption:

Water can be removed from the air by use of silica gel, activated alumina, or molecular sieve. Silica gel has a very high capacity for water and can be reactivated at a relatively low temperature. However, it will not produce the very low dewpoint that is attainable through the use of fresh molecular sieve.

When using an adsorbent to control humidity, the air will become too dry if all of the gas from an 18 cfm module is passed through the adsorbent. (See Section I, Fig. I-2) In this case it will be necessary to rehumidify the air either by returning some of the moisture laden gas to the vessel when the adsorbent is reactivated or by separate humidification of the gas downstream of the adsorber.

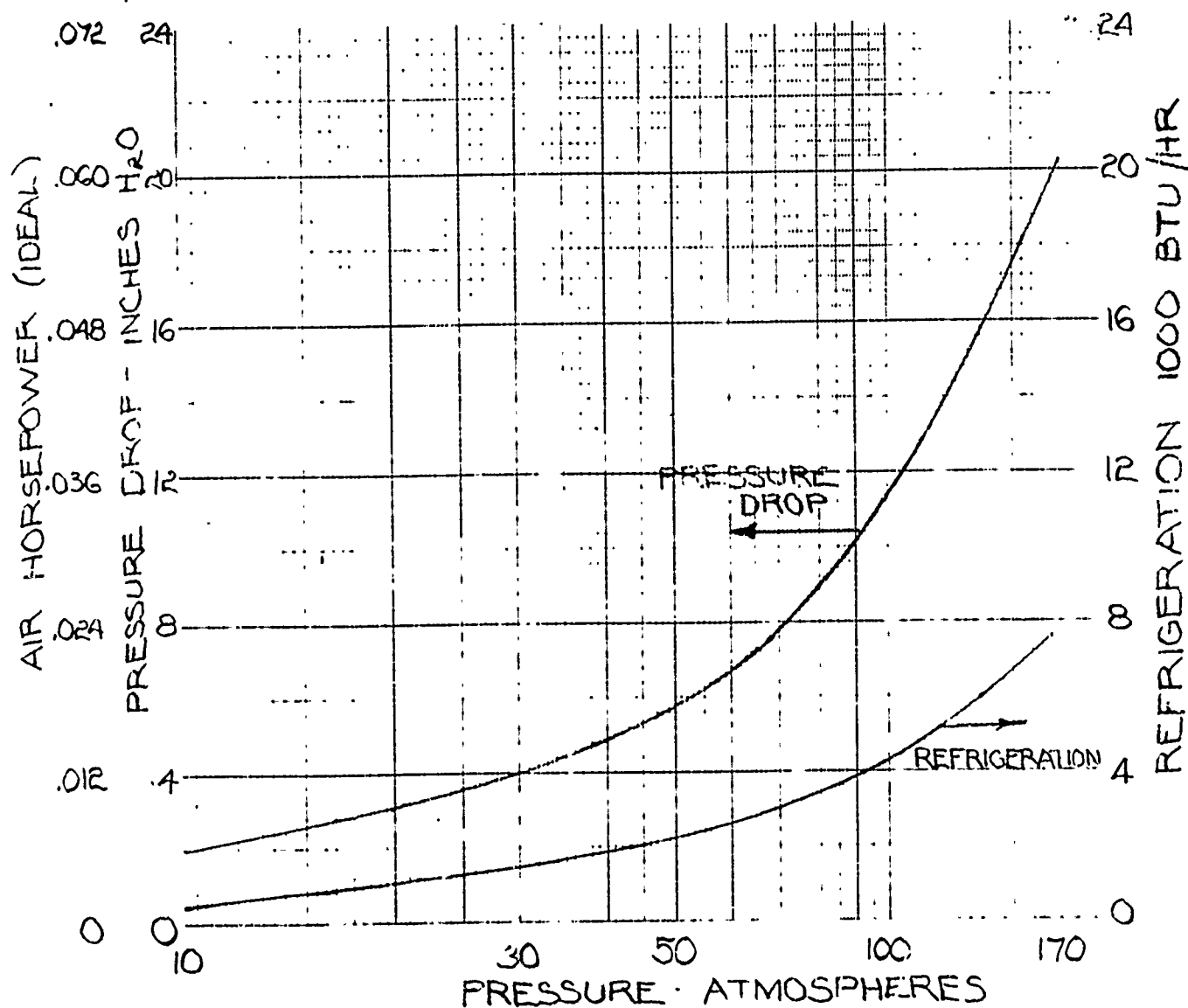
An alternative to this would be to circulate only a part of the gas through the drier section of the environment control system.

Pressure drop and adsorbent capacities for water of various materials are given in Section IV of this report.

#### E. $CO_2$ Removal by Adsorption:

The use of an adsorbent to remove carbon dioxide is attractive in that

SERRATED FIN  
 $5\frac{1}{2}$ ' LONG,  $5 \times 5$ " CROSS SECTION  
 VEL. -  $4'$ /SEC FLOW - 18 CFM  
 AT -  $3^\circ$  F.



HEAT EXCHANGE DEHUMIDIFICATION  
3 MAN MODULE

FIG. V-2

the system can be regenerated, eliminating the need to replenish the material as is necessary in a chemical removal system. (Baralyme or soda lime) The material most suitable for adsorption of CO<sub>2</sub> appears to be 5A Molecular Sieve, (Linde Div., Union Carbide Corp. Type 5A Molecular Sieve).

In order to effectively remove CO<sub>2</sub> by adsorption it is necessary to have extremely dry gas since molecular sieve will preferentially adsorb moisture. Moisture in a gas will displace any CO<sub>2</sub> that has been adsorbed. Therefore the gas must remain dry until the CO<sub>2</sub> is desorbed. A system using molecular sieve is being used in submarines by the French and by Great Britain. The main disadvantage of this type of system is that it usually requires a very high reactivation temperature in order to effectively remove all of the water (500 to 600°F).

An interesting cycle using adiabatic desorption has been proposed for a space application (see Ref. 2 and 3). Essentially this is a method of using the adsorbent inefficiently with regard to the pounds of material adsorbed per pound of adsorbent. A "pressure swing" cycle is used, reducing the adsorbent bed pressure to desorb CO<sub>2</sub> and recycling very frequently. In this case a 15 minute cycle adsorb-desorb cycle was used. The readily available vacuum of space simplified the equipment required.

The test results shown in Ref. 2 are interesting in that this system effectively moved moisture and maintained a system outlet partial pressure of CO<sub>2</sub> less than 1-1/2 millimeters for more than two months test time all without the need for a high temperature reactivation. The data would seem to indicate a moderate temperature-pressure swing cycle might be used very effectively to enhance the adsorption capability of such a system.

In addition, some tests of this unit made at the Marshall Space Center, Huntsville, have indicated the removal of Ammonia, Methyl Chloride and other trace contaminants. Carbon monoxide and Hydrogen were also tested but not adsorbed, as might be expected due to the low critical temperatures of these gases.

Data on adsorption capacity and pressure drop for 5A Molecular Sieve is given in Section IV of this report.

#### F. CO<sub>2</sub> Removal by Chemical Reaction:

The most common method of removing CO<sub>2</sub> is by recirculating the gas through a chemical that will react with the carbon dioxide (usually baralyme or soda lime).

These materials are effective and will be used as a "back-up" purification system for the High Pressure Research Facility. In the case of chemical reaction, water will be liberated. Therefore any humidity removal system should be placed downstream of the reaction. A cu. ft. of water vapor is produced for every cubic foot of carbon dioxide gas removed from the air for baralyme, soda lime and lithium hydroxide.

Although the data varies somewhat, it appears that the usual efficiency of baralyme or soda lime will result in a capacity of 20 lbs. of CO<sub>2</sub> per hundred pounds of chemical (see Ref. 4 and 5). Therefore, for a three man mission generating 12 lbs. of CO<sub>2</sub> per day, 60 lbs. per day would be required (about 1 cu. ft.). Data on pressure drop and transfer rate for solid granular chemicals is given in Section IV.

#### G. System Blower:

The 18 cfm system does not require very stringent performance from the air compressor. Several commercially available blowers would satisfy the capacity and pressure head requirements. However, these have the disadvantage of very high noise level and relatively large bulk. In addition, since blowers are usually designed for air at one atmosphere, a larger motor will be required for the more dense gas at high pressure.

There are several small blowers used for pipe organs designed to be very quiet. This is accomplished by careful design of the impeller and care in balancing the blower-motor unit. In addition sound adsorbing material is placed at critical places in the stream flow. While these would be acceptable from a noise and performance standpoint, the motor and materials of construction are not considered acceptable in the confined high pressure environment of a diving chamber.

It is proposed that a positive displacement, low pressure pump would be most suitable to this application due to the low flow that is required. This could be in the form of a multiple cylinder compressor or a bellows type system. Since this operates at low speed, the noise level should be very acceptable. A second advantage of this approach is that it could be manually operable for emergency use in case the diving system would fail.

A magnetically coupled drive will be used in the University High Pressure Research Facility. This will have the motor and all wiring located outside of the chamber and coupled to the blower (or crank) directly or by means of a pulley system within the pressure vessel.

#### References:

1. "An Experimental Investigation and System Design for Humidity and Carbon Dioxide Level Control Using Thermal Radiation", John S. Maulbetsch, AMRL-TR-68-174. Available from Clearinghouse, CFSTI, 5285 Port Royal Rd., Springfield, VA 22151.
2. Joseph B. Gillerman "A Regenerative Carbon Dioxide Removal System for the AAP Cluster". Society of Automotive Engineers Paper 690626 presented at National Aeronautic and Space Engineering & Manufacturing Meeting, Los Angeles, California Oct. 6-10, 1969.



3. "Skylab - Part 3 - Life Support Systems," G. D. Hopson, J. W. Little and W. C. Patterson, Mechanical Engineering Vol. 94, No. 5 May 1972 pp 35-40.
4. "Soda Lime Handbook", Mallinckrodt Chemical Works, St. Louis, Missouri.
5. "A Study of Carbon Dioxide Gas Adsorption" National Cylinder Gas, 840 North Michigan Ave., Chicago, Illinois 60611.

## VI. Recommended System and Program SUNYAB - High Pressure Research Facility

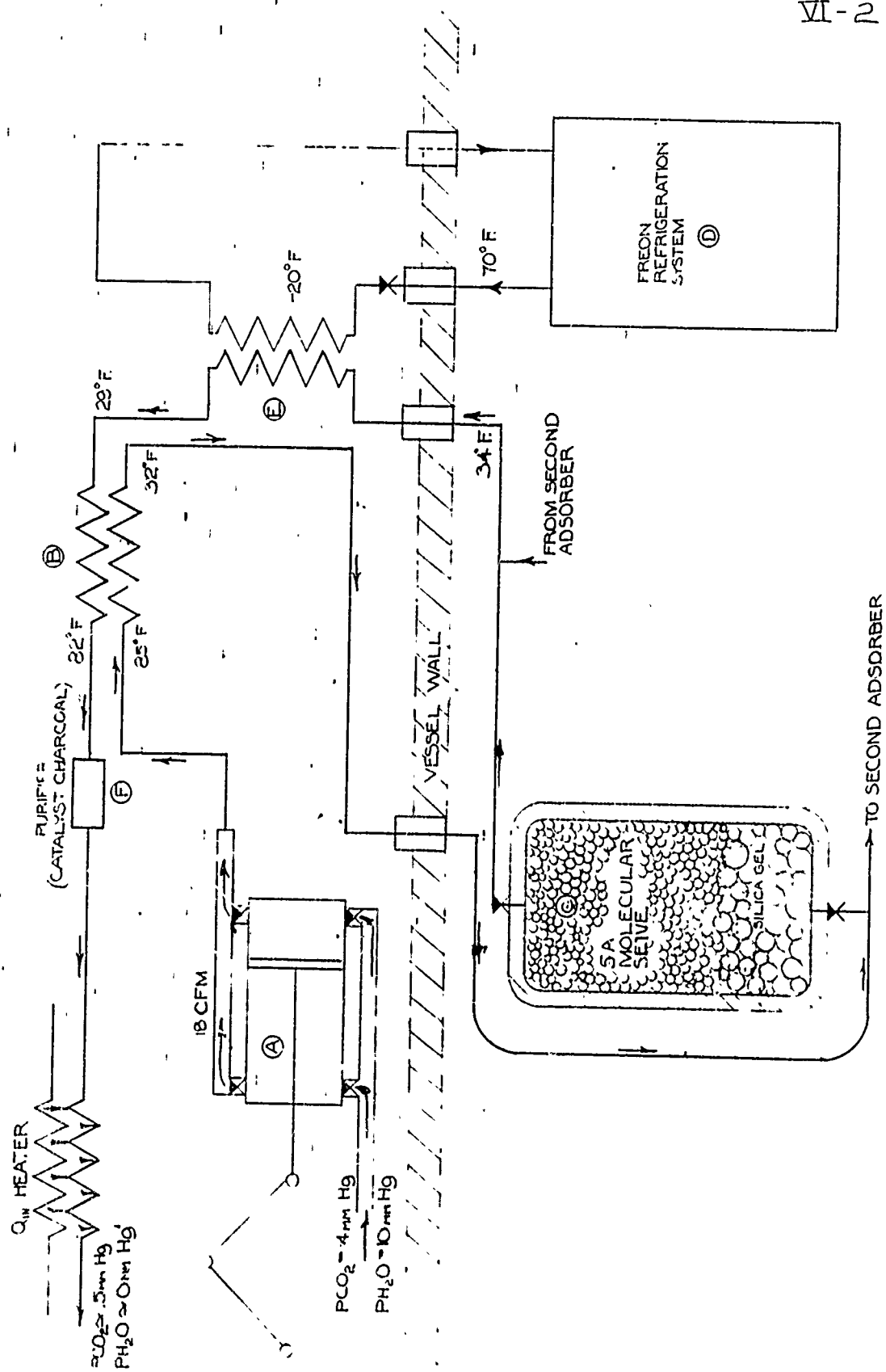
### A. Main System:

The main flow loop for removal of CO<sub>2</sub> and control of humidity is a combination system. A countercurrent heat exchanger is used to remove some of the water and to lower the temperature of the gas flowing to the adsorbent bed. Silica gel is used to remove essentially all of the remaining water. The capacity of the silica gel is enhanced at the 33°F gas temperature by a factor of 3 to 5 times over the equivalent capacity at 85°F. Following the silica gel and in the same adsorbent bed is a large section containing Type 5A Molecular Sieve to remove carbon dioxide. Refrigeration is supplied after the adsorbent bed using a conventional freon refrigeration unit. Locating the cooler downstream of the adsorber permits cooling the gas below the freezing point without the difficulty of having to defrost the cooler. The cold gas is returned to the countercurrent heat exchanger where it is warmed almost to chamber temperature, passed through a small bed of Hopcolite and charcoal, and returned to the chamber. Heat will be added to the chamber (in the heater coil) to make up for the heat removed by the cooling coil. The environment control system is shown schematically in Fig. VI-1.

The heat exchanger and cooling sections are located within the high pressure vessel, thus permitting the use of standard aluminum plate and fin heat exchangers for the countercurrent exchanger and light wall vessel for the cooler. Originally, it was planned to locate the adsorbent beds within the chamber. However, it was found that there would be no saving in weight since these adsorbent beds will be vacuum pumped and would have to be designed for high external pressure if located inside. The additional pressure drop to flow through the piping in the vessel wall is not prohibitive because of the low flows involved and small piping and valves (1-1/4 PS) can be used. Other advantages in locating the units on the outside of the chamber are saving of valuable test space, ease of reacting and the improvement of insulation around the adsorbent due to the lower thermal conductivity of air compared to helium.

Reactivation of the adsorbent bed is unconventional. Initially the adsorbent bed gas will be vented into a storage receiver. Since most of the water and CO<sub>2</sub> will be held on the adsorbent the residual gas will be essentially all helium and oxygen and can be recompressed and returned to the chamber or to storage banks. The adsorbent bed will be repressurized with helium or a helium-oxygen mixture before returning it to the control loop. This will avoid a change in chamber pressure when switching adsorbers.

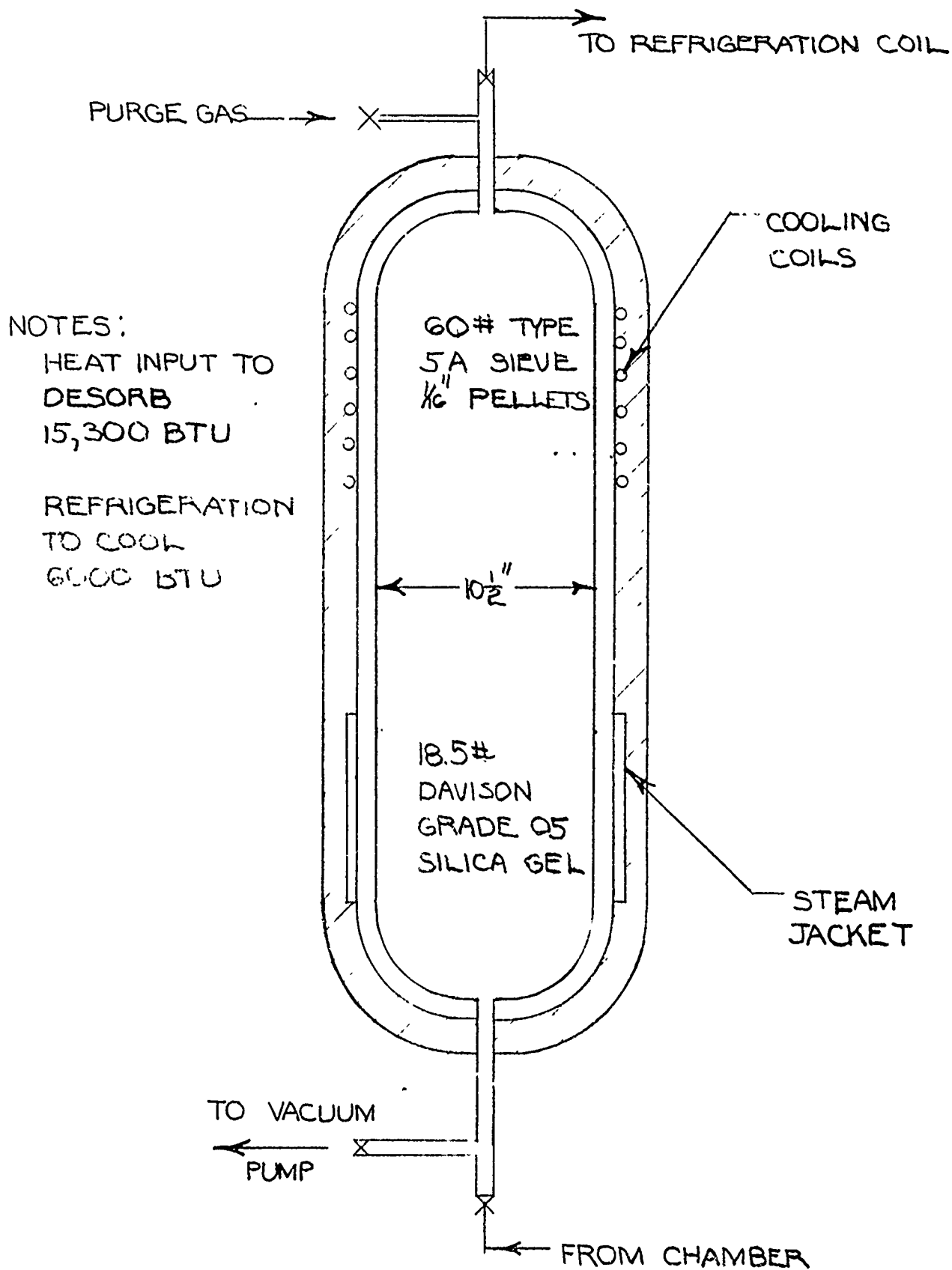
When the pressure has been reduced to atmospheric, the bed will be heated and vacuum pumped to remove the adsorbed water and CO<sub>2</sub>. With



VI-2

SCHEMATIC - MAIN SYSTEM FIG. VI-1

Fig II-2  
DESORPTION CYCLE



vacuum pumping, only a modest temperature (100 to 150°F) will be required to recondition the adsorbents. A small gas purge of dry nitrogen will be introduced to maintain the adsorbent bed pressure above the transition pressure of the silica gel (about 2 mm Hg). This will assure a flow of gas and contaminants out of the bed through the silica gel end and eliminate back flow of moisture to the Molecular Sieve. A gas ballast vacuum pump or cold trap will be required to prevent contamination of the vacuum pump with the large amount of water vapor being pumped from the bed. The reactivation cycle is shown diagrammatically in Fig. IV-2.

The control loop will be sized for a three man module. This will use 18 cfm during the day time, resulting in an expected CO<sub>2</sub> level between 2.4 and 4 mm of Hg. At night the system will run at one-half flow, 9 cfm. The lower flow will reduce the refrigeration requirement and have a lower noise level. Nine cfm will result in a CO<sub>2</sub> level of just under 2 mm Hg due to the lower metabolic rate when the occupants are sleeping (see Fig. I-1).

The basic calculations for the main system heat exchanger and adsorber design are appended to this section.

#### B. Pass Through Lock Module - High Pressure Research Chamber:

A back up system to remove CO<sub>2</sub> in the event of the primary system failure is shown in Fig. VI-3. This again is a "half day" charge using baralyme to remove carbon dioxide and silica gel to remove part of the water. The back up system canister will be inserted in the pass through lock. In the case of manned chamber occupancy the connection to the module can be made manually after pressurizing and opening the lock inner door. For animal experimentation, it will be necessary to perform these operations remotely from outside of the chamber. Calculations on adsorbent capacity are appended to this section.

An alternate system using a blower in place of the silica gel section will be designed for use in the event of failure of the primary blower or magnetic drive in the chamber.

#### C. Future Program:

Small scale tests are needed to verify the "breakthrough" characteristics of the silica gel-molecular sieve combination. This will include tests at 10, 50 and 100 atmospheres pressure using 1/2 atmosphere pressure O<sub>2</sub>, 4 mm Hg CO<sub>2</sub>, 5 mm Hg H<sub>2</sub>O and helium.

This gas will be cooled to 32°F and passed through a sample cylinder containing the appropriate ratio of silica gel and molecular sieve sections. The gas will be analyzed at the end of the silica gel and at the outlet for pressure of CO<sub>2</sub> and H<sub>2</sub>O. The sample bottle will then be heated to 100 - 120°F and desorbed, followed by cooling and another test. This will be continued until the adsorbent capacity

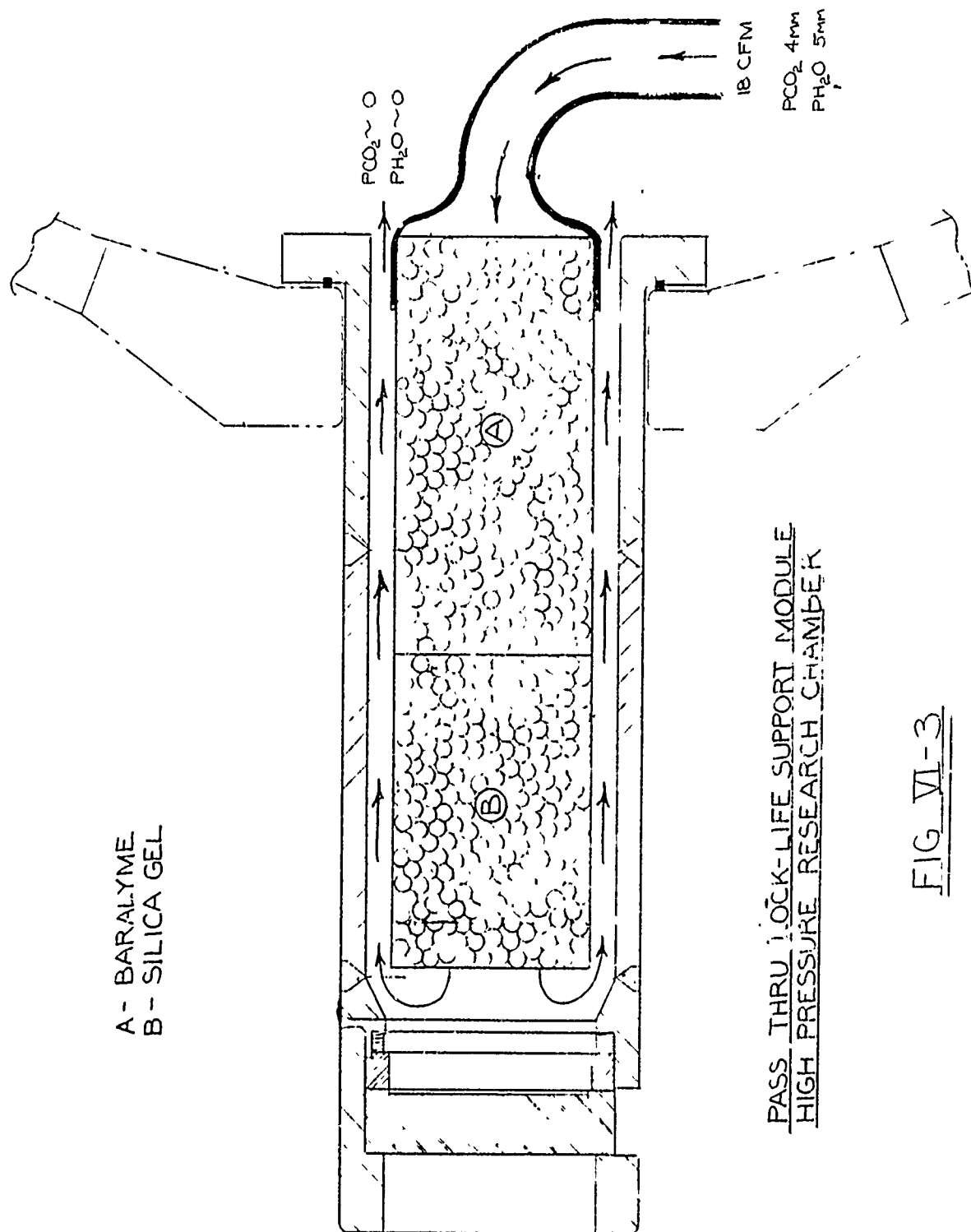


FIG VI-3

shows signs of deterioration.

Figure VI-4 shows the test arrangement. The estimated cost for this work is:

|                         |          |               |
|-------------------------|----------|---------------|
| Apparatus               | Design   | \$ 400.00     |
|                         | Purchase | 600.00        |
| Gases & Liquid Nitrogen |          | 200.00        |
| Technician 4 weeks      |          | 1600.00       |
| Analysis of results     |          | <u>600.00</u> |
| Total                   |          | \$3400.00     |

Detail design of the heat exchangers, pressure vessels, blower and refrigeration system along with the interconnecting piping must be completed prior to procurement and installation. The estimated cost of the equipment and design is (letters refer to items on Figure VI-1):

|   |                 |
|---|-----------------|
| A. Blower or Pump                               | \$ 500.00       |
| B. Plate and fin heat exchanger                 | 2,200.00        |
| C. Adsorbent bed (2 required @ 1200)            | 2,400.00        |
| D. Refrigeration system                         | 800.00          |
| E. Cooler Heat Exchanger                        | 600.00          |
| F. Purifier                                     | 300.00          |
| Vacuum Pump                                     | 600.00          |
| Piping, fittings and valves                     | <u>600.00</u>   |
| Total Parts                                     | \$ 8,000.00     |
| Design  | <u>1,400.00</u> |
|   | \$ 9,400.00     |
| Assembly & Installation<br>(Technician 4 weeks) | <u>1,600.00</u> |
| Total   | \$11,000.00     |

shows signs of deterioration.

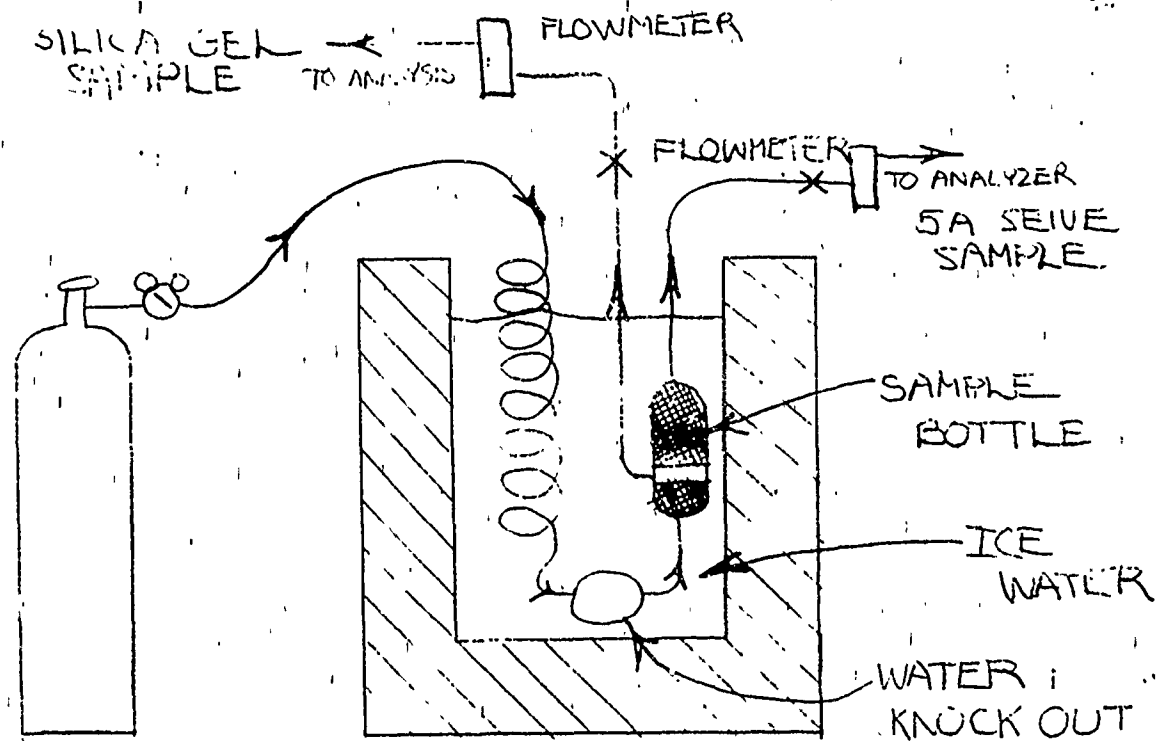
Figure VI-4 shows the test arrangement. The estimated cost for this work is:

|                         |          |               |
|-------------------------|----------|---------------|
| Apparatus               | Design   | \$ 400.00     |
|                         | Purchase | 600.00        |
| Gases & Liquid Nitrogen |          | 200.00        |
| Technician 4 weeks      |          | 1600.00       |
| Analysis of results     |          | <u>600.00</u> |
| Total                   |          | \$3400.00     |

Detail design of the heat exchangers, pressure vessels, blower and refrigeration system along with the interconnecting piping must be completed prior to procurement and installation. The estimated cost of the equipment and design is (letters refer to items on Figure VI-1):

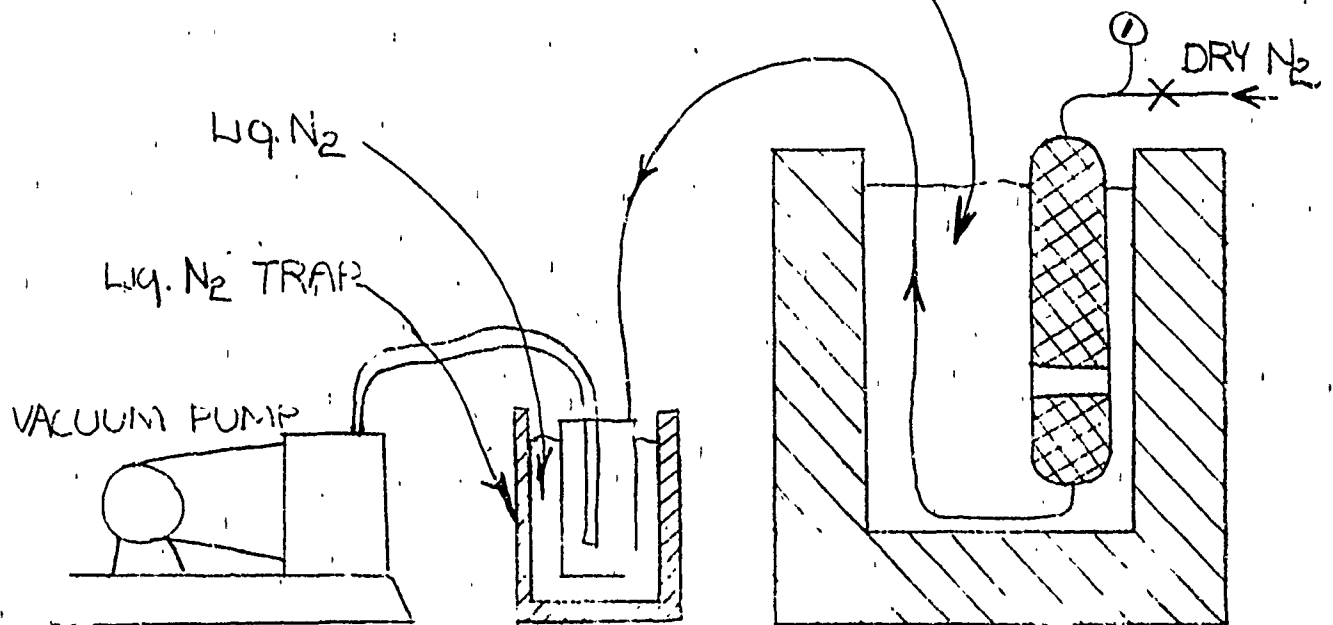
|   |                 |
|---|-----------------|
| A. Blower or Pump                               | \$ 500.00       |
| B. Plate and fin heat exchanger                 | 2,200.00        |
| C. Adsorbent bed (2 required @ 1200)            | 2,400.00        |
| D. Refrigeration system                         | 800.00          |
| E. Cooler Heat Exchanger                        | 600.00          |
| F. Purifier                                     | 300.00          |
| Vacuum Pump                                     | 600.00          |
| Piping, fittings and valves                     | <u>600.00</u>   |
| Total Parts                                     | \$ 8,000.00     |
| Design  | <u>1,400.00</u> |
|   | \$ 9,400.00     |
| Assembly & Installation<br>(Technician 4 weeks) | <u>1,600.00</u> |
| Total   | \$11,000.00     |





ADSORPTION CYCLE

HOT WATER (100°F - 120°F)



DESORPTION CYCLE

FIG. VI-4

SMALL SCALE ADSORBENT CAPACITY TEST

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 TONAWANDA, NEW YORK 14150  
 (716) 832-6554

# OPERATING CONDITIONS:

3 MAN MODULE - EACH MAN (SEE TABLE I-1)

| WORK  | HRS/DAY | $\frac{CO_2}{\#/h} \#/day$ |     | $\frac{H_2O}{\#/h} \#/day$ |      | $\frac{O_2}{SCFH/h} SCFH/day$ |      |
|-------|---------|----------------------------|-----|----------------------------|------|-------------------------------|------|
| HEAVY | 6       | .38                        | 2.3 | .18                        | 1.08 | 3.75                          | 22.5 |
| LIGHT | 10      | .13                        | 1.3 | .061                       | .61  | 1.3                           | 13.0 |
| SLEEP | 8       | .06                        | .6  | .023                       | .18  | .63                           | 5.1  |
| TOTAL |         | 4.1#/day                   |     | 1.87#/day                  |      | 40.6 SCFH/day                 |      |

FOR 3 MEN -

$$\text{AVE DAYTIME } CO_2 = \frac{3(2.3 + 1.3)}{6 + 10} = .675 \#/h$$

$$* \text{ " " } H_2O = \frac{3(1.08 + .61)}{6 + 10} = .315 \#/h$$

$$\text{ " " } O_2 = \frac{3(22.5 + 13)}{6 + 10} = 6.65 \text{ SCFH}$$

$$\text{AVE NIGHT } CO_2 = 3 \times .06 = .18 \#/h$$

$$\text{ " " } H_2O = 3 \times .18 = .54 \#/h$$

$$\text{ " " } O_2 = 3 \times .63 = 1.89 \text{ SCFH}$$

\* NOTE THE DAYTIME  $H_2O$  LEVEL SHOULD BE INCREASED TO  $.52 \#/h$  TO ACCOUNT FOR  $1.1 \#/\text{MAN DAY}$  SKIN EVAPORATION.

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 TONAWANDA, NEW YORK 14150  
 (716) 832-6554

DESIGN ADSORBENT BEDS TO BE  
 DESORBED 1 TIME EVERY 24 HRS

TOTAL CO<sub>2</sub> = 12 # / DAY

EACH BED MUST ADSORB 6 # CO<sub>2</sub>

LOOP FLOW - 18 CFM DAYTIME  
 9 CFM NIGHT

HEAT EXCHANGER (SEE SECTION III):

AT 18 CFM ASSUME VELOCITY = 3.5 /s

Flow AREA REQ'D / SIDE =  $\frac{18}{60 \times 3.5} = .086 \text{ ft}^2 = 12.4 \text{ in}^2$

TOTAL AREA  $\approx 25 \text{ in}^2$

LENGTH (FOR 170 ATA) = 5', 2"

| PRESSURE<br>ATA | $P$<br>#/cu ft | $C_p$<br>BTU/#°F | $\Delta P$<br>"H <sub>2</sub> O | $\Delta T$<br>°F | REFRIG<br>BTU/HY |
|-----------------|----------------|------------------|---------------------------------|------------------|------------------|
| 10              | .135           | .95              | 2.8                             | 1.6              | 220              |
| 50              | .535           | 1.174            | 5.7                             | 2.2              | 1460             |
| 90              | .935           | 1.206            | 9.3                             | 2.4              | 2950             |
| 130             | 1.335          | 1.219            | 12.4                            | 2.6              | 4600             |
| 170             | 1.735          | 1.226            | 15.4                            | 3.0              | 6900             |

NIGHT REFRIG REQMT  $\approx \frac{1}{2}$

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 ENGINEERING CONSULTANT  
 117 CORNWALL AVENUE  
 TONAWANDA, NEW YORK 14150

(716) 832-6554

## ADSORBER DESIGN (SEE SECTION V):

### ADSORBER A - DAYTIME

Flow 18 CFM,  $\text{CO}_2 \sim .675 \frac{\#}{\text{hr}}$   
 $\text{H}_2\text{O}$  - SATURATED AT  $32^\circ\text{F}$   
 $= 2 \text{ grains/cu ft}$

TIME BEFORE DESORBING:

$$\frac{6}{.675} = 9 \text{ HOURS}$$

$\therefore$  ADSORBER B 15 Hr Ads., 9 Hr Des.

### WATER REMOVAL REQ'D

$$\text{CFM} \times 60 \times 9 \times \frac{\text{grains}}{7000} \\ = \frac{18 \times 60 \times 9 \times 2}{7000} = 2.76 \#$$

ASSUME CAPACITY SILICA GEL  
 IS 15% BY WT

$$\text{SILICA GEL REQ'D} = \frac{2.76}{.15} = 18.5 \#$$

$$P = 45 \frac{\#}{\text{cu ft}} \quad \text{NEED} \sim .41 \text{ cu ft}$$

### $\text{CO}_2$ REMOVAL

TYPE 5A MOLECULAR SIEVE  $\sim 10\%$  CAP

$$\text{NEED} \frac{6}{.1} = 60 \# \text{ SIEVE}$$

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JOHN M. CANTY, P. E.  
 ENGINEERING CONSULTANT  
 117 CORNWALL AVENUE  
 TONAWANDA, NEW YORK 14150

(716) 832-6554

### ADSORBER DESIGN (CONT):

ASSUME SUPERFICIAL VELOCITY  $.5'/\text{SEC}$

$$\text{AREA} = \frac{18}{(60)(.5)} = .6 \text{ ft}^2$$

USE SCHED 140 - 12" PIPE - ID = 10.5"  
 OD = 12.5" AREA = .601 ft<sup>2</sup>

$$\text{SILICA GEL SECTION} = \frac{.41}{.6} = .68 \text{ ft}$$

$$\text{MOLECULAR SIEVE SECTION} = \frac{1.2}{.6} = 2 \text{ ft}$$

OVERALL LENGTH  $\sim 3 \frac{1}{2} \text{ FT}$

DESORBING - HEAT TO  $\sim 120^\circ\text{F}$

WT OF SHELL  $\sim 530 \#$   
 HEAT CAPACITY  $\approx 53 \text{ BTU}/^\circ\text{F}$

$$\begin{aligned} Q \text{ TO HEAT SHELL} &= 53(120 - 32) \\ &= 4600 \text{ BTU} \end{aligned}$$

$$\begin{aligned} Q \text{ TO HEAT ADSORBENT} &\approx .2(60 + 18.5)(120 - 32) \\ &= 1400 \text{ BTU} \end{aligned}$$

$$\begin{aligned} Q \text{ TO REMOVE WATER (ASSUME } 2500 \text{ BTU}/\# \text{ WATER)} \\ &= 2500 \times 2.76 \\ &= 6900 \text{ BTU} \end{aligned}$$

$$\begin{aligned} Q \text{ TO REMOVE CO}_2 \text{ (ASSUME } 200 \text{ BTU}/\# \text{ CO}_2) \\ &= 1200 \text{ BTU} \end{aligned}$$

$$Q \text{ HEAT LOSS} = 1200 \text{ BTU}$$

$$\text{TOTAL HEAT } 15,300 \text{ BTU}$$

TITLE: ENVIRONMENTAL SYSTEM  
DESIGN CALCULATIONS  
BY: JMC DATE: \_\_\_\_\_

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JOHN M. CANTY, P. E.  
ENGINEERING CONSULTANT  
117 CORNWALL AVENUE  
TONAWANDA, NEW YORK 14150  
(716) 832-6554

### DESORPTION (CONT)

TOTAL HEAT REQ'D 15,300 BTU

IF REACTED OVER A 4 HR PERIOD

WOULD NEED 3,800 BTU/hr ~ 1.2 KW

COOLING TO 32°F

|           |                 |       |
|-----------|-----------------|-------|
| SHELL     | 4600 BTU        |       |
| ADSORBENT | 1400 BTU        |       |
|           | <u>6000 BTU</u> | TOTAL |

GAS LOSS ON BLOWDOWN APPROX  
50% OF VOLUME OR ~.8 CU FT

USE DAVIDSON GRADE 05 SILICA GEL  
& LINDE TYPE 5A SIEVE #6 PELLETS

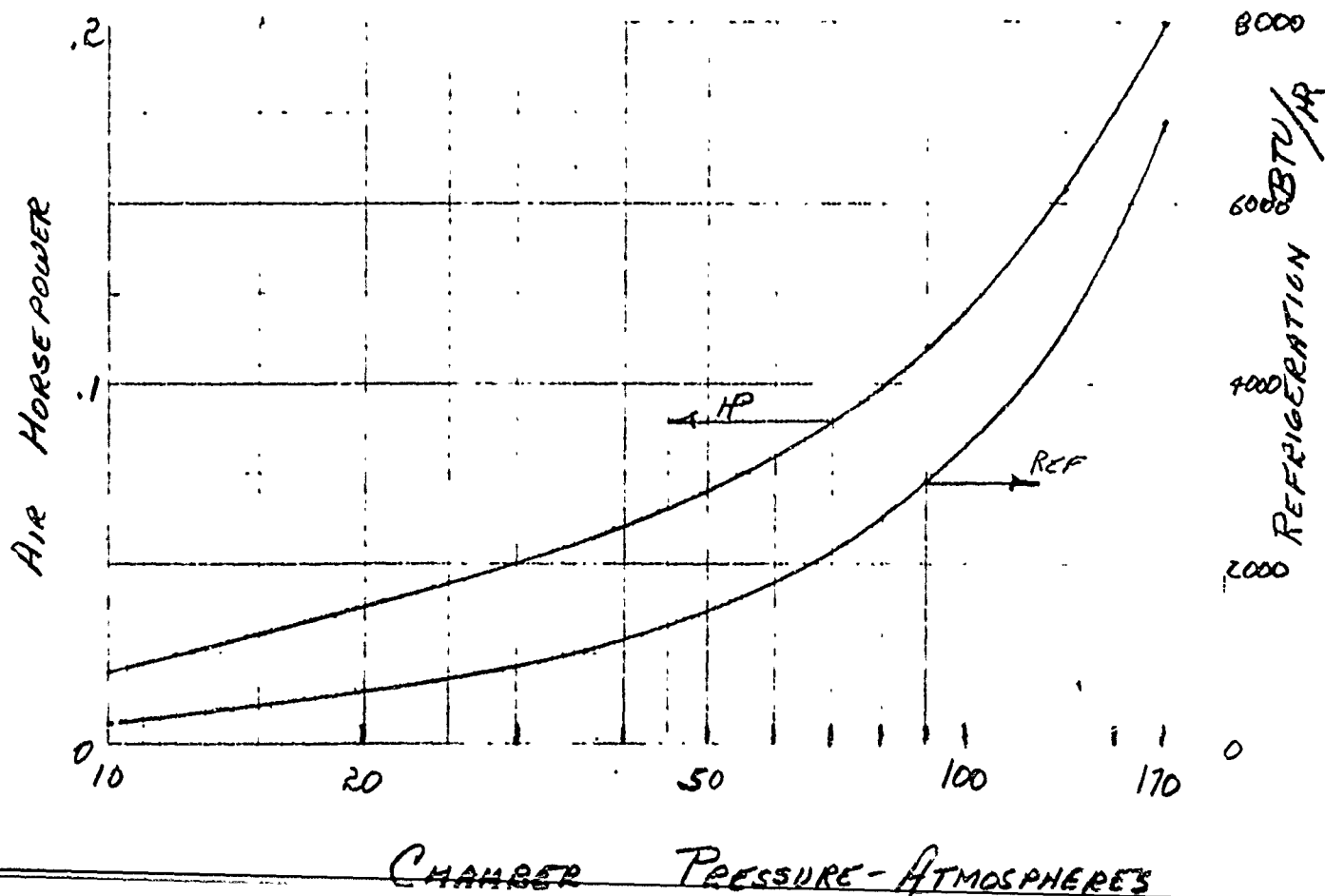
| PRESSURE | DROP              | THROUGH BED              |
|----------|-------------------|--------------------------|
| P        | $\Delta P$        | $\Delta P$ PIPING (~10') |
| ATMOS    | "H <sub>2</sub> O | "H <sub>2</sub> O        |
| 10       | 2.3               | 2.2                      |
| 50       | 10                | 8.7                      |
| 90       | 15                | 15.2                     |
| 130      | 21                | 21.5                     |
| 170      | 28                | 28                       |

TITLE: ENVIRONMENTAL SYSTEM  
DESIGN CALCULATIONS  
 BY: JMC DATE: \_\_\_\_\_

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 JOHN M. CANTY, P. E.  
 ENGINEERING CONSULTANT  
 117 CORNWALL AVENUE  
 TONAWANDA, NEW YORK 14150  
 (716) 832-6554

DESIGN SUMMARY - 18 CFM

| PRESSURE<br>ATMOS | TOTAL $\Delta P$<br>"H <sub>2</sub> O | AIR HP<br>(IDEAL) | REFRIG<br>BTU/H |
|-------------------|---------------------------------------|-------------------|-----------------|
| 10                | 7.3                                   | .02               | 220             |
| 50                | 24.4                                  | .07               | 1460            |
| 90                | 39.5                                  | .11               | 2950            |
| 130               | 54.9                                  | .154              | 4600            |
| 170               | 71.4                                  | .2                | 6900            |



TITLE: PASS THRU LOCK MODULE

JOHN M. CANTY, P. E.  
ENGINEERING CONSULTANT  
117 CORNWALL AVENUE  
TONAWANDA, NEW YORK 14150

BY: J M C DESIGN CALCULATIONS

DATE: \_\_\_\_\_

(716) 832-6554

SEE FIG II-3

PASS THRU LOCK MODULE - CHANGE EVERY  
1/2 DAY - 6# CO<sub>2</sub> (SEE PAGES II 889)

MAXIMUM WATER REMOVAL - MOISTURE FROM  
OCCUPANTS DURING DAY .51#/hr OR  
FOR 9 hrs (SEE P II-10) 4.6#

MOISTURE FROM CO<sub>2</sub> REACTION  $18\text{CO}_2 \rightarrow 18\text{H}_2\text{O}$

$$\frac{M_{\text{H}_2\text{O}}}{M_{\text{CO}_2}} \times W_{\text{CO}_2} = \frac{18}{44} \times 6 = 2.5\#$$

TOTAL WATER 7.1#

BARALYME REQ'D  $\frac{6}{.2} = 30\# \sim .47\text{cu ft}$

MODULE DIAMETER 8"

LENGTH OF BED =  $\frac{.47}{\frac{\pi}{4}(\frac{8}{12})^2} = \underline{\underline{1.35\text{ft}}}$

TOTAL MODULE LENGTH 2.35' (28")

VOL SILICA GEL =  $\frac{\pi}{4}(\frac{8}{12})^2 = .35\text{ cu ft}$

WT = 16#

This will remove about  $.35 \times 16 = \underline{\underline{5.5\# \text{H}_2\text{O}}}$

PART OF THE GAS MUST BYPASS SILICA GEL

